CONTROL AND INSTRUMENTATION OF A BATCH JIG FOR IMPROVED PERFORMANCE

By

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VINEET KUMAR DWIVEDI

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With love to ....

R K (The youngest person in my family)

Acknowledgements

With the submission of this thesis my academic career in MME at IIT Kanpur has (possibly) come to an end. I taken this opportunity to express my sincere gratitude to this place where I have spend many years of my academic life ; First as a B. Tech. Student, then as a PA and finally as an M. Tech. Student. All my confidence, knowledge and skills have been nurtured by this place.

The successful completion of this work has been possible only by the support, encouragement and excellent guidance of my thesis supervisor Prof. B. K. Mishra . The work that has been carried out was tedious and it was the support of Mr. Surendra Agnihotri, Mr. Avinash Sahani that made it possible in a very short span of time.

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Above all it was the support and blessings of my parents that is always with me and is reflected in the present work also.

CERTIFICATE

This to certify that the work contained in the thesis entitled **CONTROL AND INSTRUMENTATION OF A BATCH JIG FOR IMPROVED PERFORMANCE** has been carried out by **Vineet Kumar Dwivedi** under my supervision and that this work has not been submitted elsewhere for a degree.

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April, 2002

Abstract

There are many method of separating the particles on the basis of their densities. Of these jigs are the most important. With the advancement in sensor technology jigs have assumed their importance once again. With the proper control a jig can stratify more particles in less time and energy compared to other gravity separation units. The present research work aims at understanding the jigging process through particle stratification.

Several improvements to the existing jigging facility provided an improved control over pulsation of water through the jig bed resulting in better stratification. These improvements primarily include: timer control program, two-way pressure adjustment to control water pulsation, recalibration of all the sensors, and a graphical interface to start the jigging process. These changes not only made it easy to operate the jig with desired frequency and amplitude but also gave a facility for recording all the parameters in real time.

With this new setup many experiments have been done to understand the effect of frequency and amplitude on the stratification behaviour of the particle bed. These experiments verified some of the theoretical models derived in this work. Also the feedback from the experiments helped in an improved control over frequency and amplitude. A preliminary experiment is also carried out to study coal separation in a jig.

In addition to the above experimental work some theoretical analysis was also made to establish the minimum fluidization velocity. This model equation correctly predicts the fluidization velocity under several operating condition. In addition it also suggests the conditions for which reverse stratification may take place.

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Chapter 1

INTRODUCTION

An important operation in mineral processing is physically separating the grains of valuable minerals (concentrates) from the gangue minerals (tailings). Most of the methods of separation used in mineral industries are based on optical and radioactive properties (sorting), specific gravity difference (dense medium separation, gravity separation), different surface properties (froth flotation), magnetic properties, electrical properties and size difference. In some cases a combination of two or more may be needed. Seperation, which uses difference in specific gravity, are one of the most commonly used because of their effectiveness, low cost; and operational simplicity.

To stratify mineral particles with different specific gravity jigging is used. As compared to other stratification processes jigging has the advantage of comparatively simple design and high throughput. It can separate particles with a difference of 0.1 in specific density. Particles with density difference of less than 0.1 gm/cc have also been separated in the recent years. For a fixed number/kind of particles the parameters for stratification may be amplitude, frequency viscosity and the density of the medium.

1.1 Description of the Jigging Process

The jigging is a separation process in which a mineral bed is pulsated by a current of water resulting in stratification of mineral particles of different specific gravity. Thus it exploits the stratification of particulate matter under the influence of hydrodynamic and gravity forces. It operates in a cyclic manner that can be explained with respect to Figure

1 where a bed of particles and fluid medium is shown. The jig cycle may be considered consisting of four stages, namely, inlet, expansion, exhaust, and compression. In the inlet stage the fluid lifts the bed *enmasse*. Near the end of the lift stroke, the particles at the bottom of the bed start falling resulting in the loosening of the bed which, in turn, causes its expansion or dilation. During the third and fourth stages of jig cycle, the flow direction of the fluid is changed and the particles resettle through the fluid. The bed collapses back to its original volume. The pulsation and suction is repeated to bring about stratification with respect to specific gravity across the bed height. Typically the water pulse (usually around 0.5-1.2 Hz) driving the separation is generated by compressed air entering and exiting the jigging chamber to generate an oscillating pulse of water through the screen plate.

The basic jig, Baum Jig, is suitable for larger feed sizes. Although the Baum Jig can clean a wide range of coal sizes, it is most effective at 10-35 mm. A modification of the Baum Jig is the Batac Jig which is used for cleaning fine particles. The particles are stratified by bubbling air directly through the particles-water mixture in this cleaning unit.

Although large scale studies of commercial jig operation have been undertaken the optimization of jigs is difficult due to (i)the time and expense to adequately sample the device and (ii)generally poor instrumentation and control at the selected operating state.

The issues most relevant to jig operation are (i) control of feed rate and distribution, across the jig (ii) variability in feed composition (iii) pulse generation to drive the separation. In addition, the pulse being generated by the compressed air is maintained by a dynamic balance between airflow rates into and out of the air chambers. In a Batac jig where the air chambers are below the jig bed plate, the natural level for water in the chambers is some distance above the top of the chamber. To further complicate matters, the resistance of the particle bed to flow of water is a major component in dissipating the energy from the water pulse. Because of the compressible nature of air, the pulse amplitude will be influenced by feedback from varying particle bed resistance.

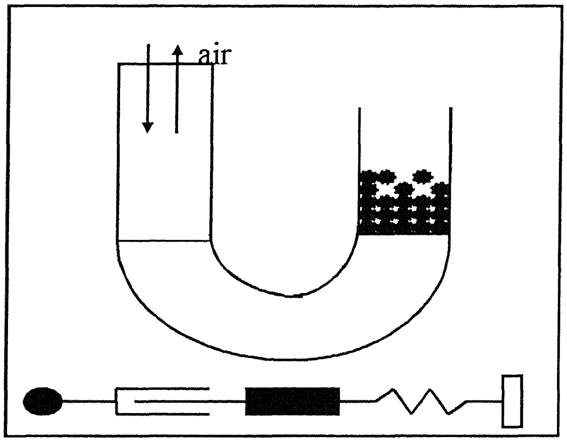


Figure 1.1 Simplified schematic of a Baum Jig system

Although this discussion paints a reasonably gloomy picture of jig operation, it must be pointed out that jigs have been operated successfully for hundreds of years with minimal control strategies. It is our contention that jig operation can be made significantly more predictable and optimal by addressing these measurement and control problems. It is with this goal in mind, and the issues and concerns raised above that a first step has been taken in developing instrumentation to assist this process.

With the advent of modern sensor technology, it has become imperative to use sensors and transducers effectively to control the process for optimum results. The controls for many instruments have been developed. Namely an in-bed nucleonic gauge for the measurement of wet bulk densities at well-defined horizons in the jig bed,[1] pressure transducers for measuring air pressures around the jig, a level sensor to measure the height of the water surface, and two three-way and one two-way valves to control the flow of air. The novel feature of these devices is their ability to resolve the time-varying nature of the measurement during a pulse (nominally 1 second) of the jig.

1.2 Current Jig Research Targets at IIT Kanpur

The purpose of jig research at the IITK is to bring a detailed engineering and scientific understanding of jig operation to the industry. The approach is threefold:

- test work to understand jig operation and material stratification
- software models to encapsulate the understanding gained of the stratification process
- instrumentation and control strategies for pilot scale and commercial jig.

The pilot jig at IITK is being used to further develop jig instrumentation and control strategies which can be quickly tested on commercial jigs through software updates to the control systems designed here.

The instruments described in this paper form a key part of the research strategy providing an empirical means to compare stratification results in both a research and commercial context. Current activities in jig control include implementing a pulse control strategy whereby the pulse prediction model will use measurements from the control system to characterize the operation of a jig and to predict the valve timings required to achieve the desired pulsation profile in each jig chamber regardless of changes in feed composition, feed rate, changes in jig cut point, and mechanical wear of valves and other components.

1.3 Brief Literature Review

This work derives the motivation from the research work already done at the IIT Kanpur and JKMRC Australia. Extensive theoretical and experimental work has been done at both these places that form the basis of this work.

Gaudin [2] was the first to describe jigging through a detailed study of the behavior of particles in a fluid medium. Mayer [3] proposed the potential energy theory which says that main driving force for stratification is the difference in PE of the stratified and un-stratified bed. This analysis has been extended by many researchers..

Rong and Lyman [4] modeled the jig bed stratification and found in their experiments that water pressure above the bed plate has a dominant effect followed by the water

displacement. The velocity and acceleration of the water have insignificant effects on the overall stratification

A good model based on the discrete element method has been given in a recent paper by Mishra and Mehrotra [5]. This microscopic model can describe motion of individual particles which results in macroscopic behavior like segregation. A three dimensional model to track the position of particles in a jig bed was also developed which graphically show the segregation after the computations are over. But the drag force taken into account in this model is modified in this work in the theoretical calculation of critical velocity needed for movement of the particle bed.

.Srinivasan, Mishra and Mehrotra [6] developed a mathematical model to simulate the particles behavior in a Jig. A software is prepared based on this model. Existence of an optimum condition is searched by using this model. Different water waveforms are taken to study the effects of waveforms on the overall stratification. The model predicted that a very high and low values of amplitudes results in poor stratification. This is doubtful. A high value of amplitude cannot result in poor stratification. Actually there is a critical amplitude above which there is no significant improvement in the stratification. Lower the amplitude, lesser will be the energy input in the system. Thus keeping the amplitude low is desired but increasing the amplitude does not have a reverse effect on stratification. This has been verified experimentally in the present work. None of the waveform taken for simulation by. Srinivasan et. al [6], matches the actual waveform observed.

A fuzzy controller for a Baum Jig has been desighned by Mishra and Chakrborty [7]. But this is theoretical only and does not have an experimental backup. The basic model used in this is the same as in [6] and [5] by Mishra. Then controller is based on CG difference which is divided into three parts namely small, medium and large. They should have divided it into 5 or 7 parts for a better control.

The fluid motion during jigging has been analyzed by Mishra and Adhikari [8]. The number of experiments performed by them is limited. They have divided the cycle into 6

parts. But this has been proved in the theoretical analysis as part of the present research work that the cycle can be divided into 3 parts without any loss of generalization. Also there was some problem in the calibration of nucleonic density gauge in their experiment because the wet bulk densities they have obtained are erroneous.

Rong and Lyman [9], in their paper on "New energy dissipation theory" have predicted and verified that the water flow in Jigging is essentially turbulent. This turbulence is necessary in transfer of energy. But in case of too low or too high turbulence, the bed stratification is worse. Thus a medium turbulence is good. This can be determined empirically for different jigs. This work also includes theoretical verification of motion being turbulent under certain conditions during jiging, which is given in the appendix

M. G. Rasul et al [1] have discussed the criterion for layer inversion. Actually the driving force for separation depends upon density, shape, size and surface roughness. Of these density is the most important. But it has been observed that when two the particle of high density is of smaller size then after a certain critical (inversion) velocity the dense particle forms the top layer as against the common notion of *"Heavier goes down"*. To avoid layer inversion particles in a narrow size range were used in the present investigation.

1.4 Motivation for Present Research

As mentioned earlier the present research work started with the existing jig set-up. The experiments that were done with the old jig setup before this work was initiated are well documented. However from the operational standpoint, the jig set-up had many drawbacks. The main drawback was that the operation proceeds with an inbuilt correlation between the amplitude and frequency of jigging which is a characteristic of the jig set-up. Therefore, frequency of pulsation could not be varied independent of the amplitude and vice versa. This proved to be a very serious drawback as only a limited number of experiments could be performed6 Also the range of frequencies was limited to 20-35 with the upper and lower limits rarely achieved. The frequency mostly varied between 28-32.

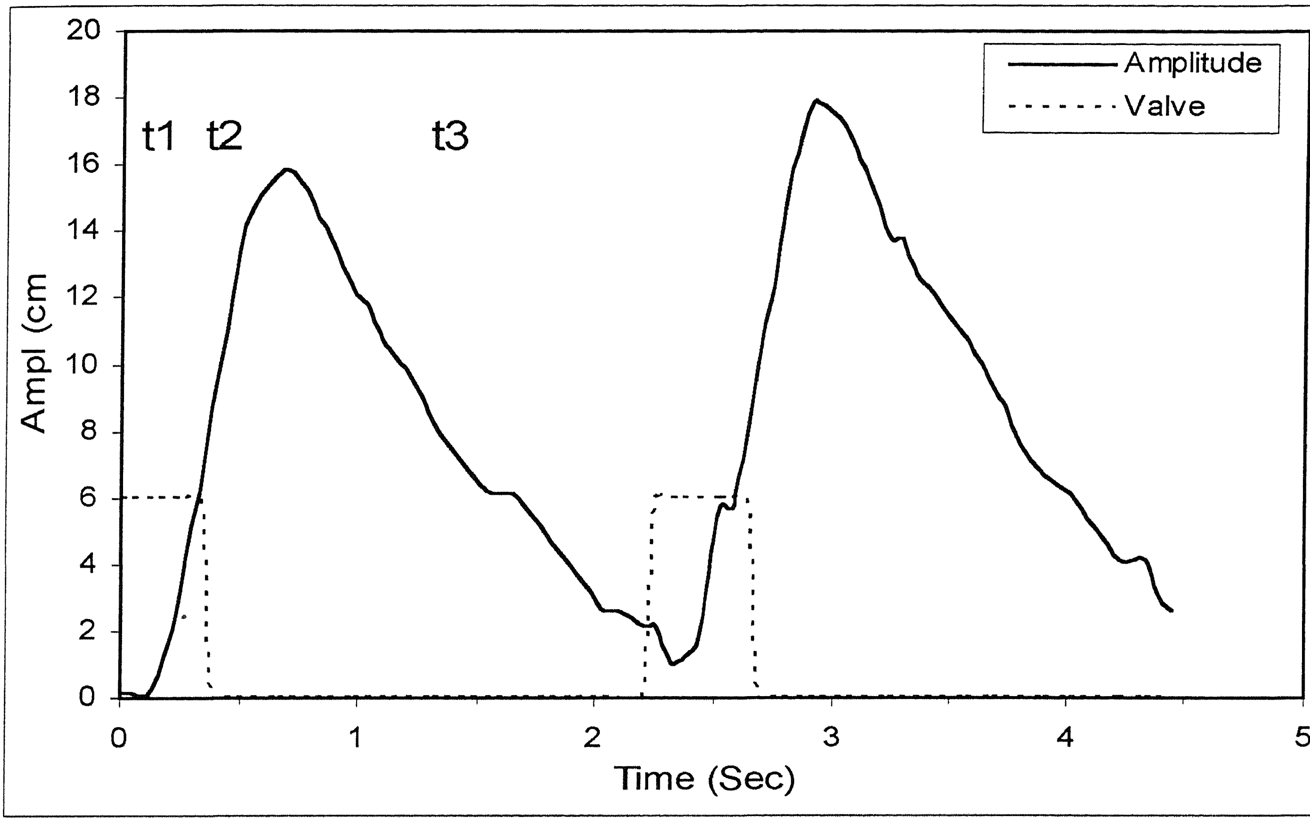


Figure 1.2 Height of the water column with time in the old jig system

The above graph represents an experiment performed with the old system. The air pressure is applied to one arm of the U-tube and particles are placed in the other arm. It is very obvious from the graph that the slope during "up" motion of the particles is very steep and the slope during "down" motion is not that steep. This is because the "down" motion is controlled by the gravity only which is much less than the pressure exerted by air during "up" motion. Here t_1 is the time-span in which the valve is open and the water motion is upwards and t_2 is the time-span in which the valve is closed but the motion is upwards due to the momentum of the water. Finally, t_3 is the time-span in which the valve is closed and the motion is downwards. t_1, t_2 and t_3 added together will give the time-period of one cycle. Now it is obvious from the graph that unless t_3 is reduced there can not be any significant improvement in the frequency of the jig.

To reduce t_3 two methods were applied. In the first method a steady back-pressure was applied to the pulsating water during the "down" cycle. This back-pressure improved the frequency significantly from around 30 to 45 cycles/min. In the second method air was used for a back-pressure to the pulsating water during the "down" cycle. This indeed proved to be very beneficial as it significantly improved the range of frequencies from 30 to 80 cycles/min. This was a big improvement and with the help of this the correlation between frequency and amplitude was broken and thus a range of frequencies from 20-80 cycles/min was obtained. This improved the scope of the experiments. The manner in which these ideas were implemented will be clearer in the later chapters.

1.5 Scope of the Thesis

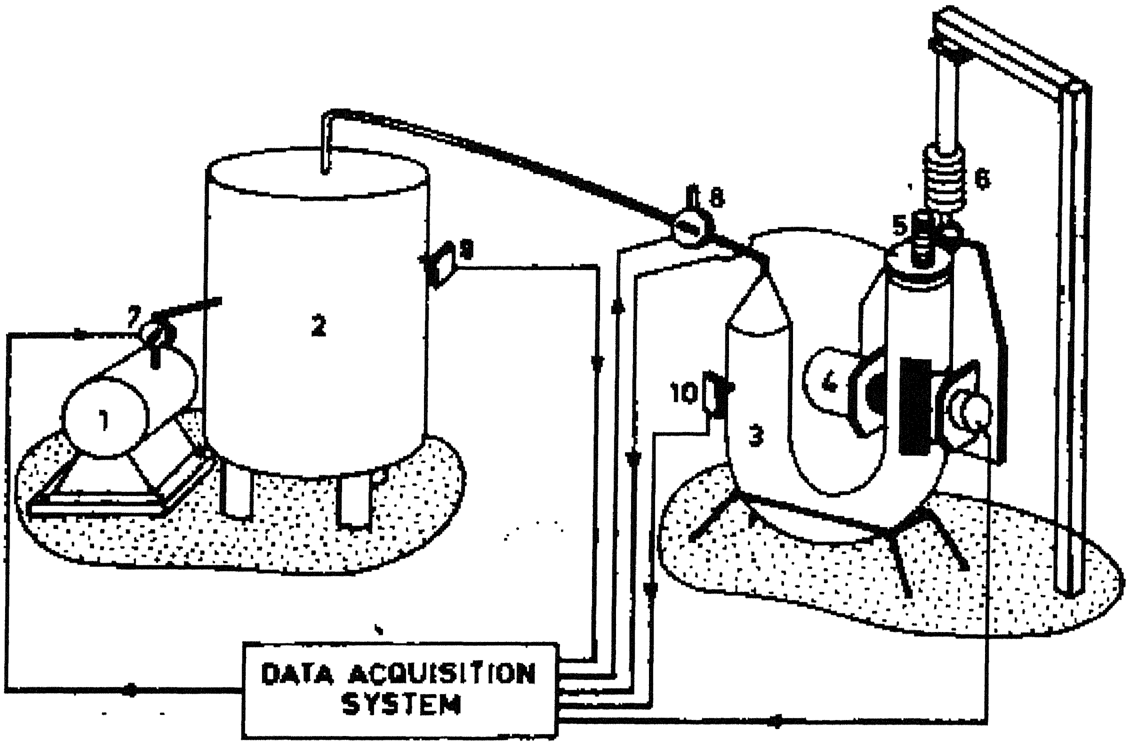
This work is organized into 5 chapters. The first chapter (which is the present chapter) gives a brief induction of the jigging process and the work done in this area. It also describes the motivation for the present work. The second chapter describes the various instruments and their calibration. It also contains step by step description of the improvements made to the old jigging system. In the third chapters the critical velocity for stratification is derived and is compared with experimental data for the same. The fourth chapter contains actual experiments done with the binary system. Two types of particles of the same size but different densities are taken. Many experiments are done at different amplitudes and frequencies to see the effect of amplitudes and frequency on the overall stratification behavior. The final and fifth chapters talks about the conclusions of the present work and also points to the directions in which future efforts should be directed.

Chapter 2

CALIBRATIONS AND SYSTEM DESCRIPTION

A batch jig system comprises of primarily the following: jigging chamber, air chamber, air compensator, the source of air supply, and instrumentation. A schematic of the original jig system is shown in figure 2.1. With reference to this figure various parts of the jigging system may be identified. The one half of the U-tube acts as the air chamber and the other half above the screen acts as the jigging chamber. Jigging takes place in a sequence of inlet and exhaust of air into and the air chamber that in turn pushes the water up and down through the jigging chamber. The air supply to the air chamber is controlled through a solenoid valve that connects the air compensator and air chamber. This valve is operated by the computer through a relay circuit.

The main drawback of this system is that downward motion of water in the jigging chamber takes place through gravity. Only the upward motion of water can be controlled by varying the pressure in the compensator. This results in a very limited range of frequencies. To overcome this inherent drawback many improvements were made to this system during the course of present investigation. It is appropriate here to discuss various instruments that had been used earlier to control the process of jigging before getting into the improvements are made as part of the present research investigation.



1. Compressor 2. Compensator 3. Jig 4. Nucleonic density gauge 5. Level sensor
6. Pneumatic Actuator 7. Two-way solenoid valve 8. Three-way solenoid valve
9. and 10. Pressure transducers

Figure 2.1. Schematic of the original experimental set-up

2.1 Description of Jigging System

A jig system comprises of various transducers to record the parameters and valves to control air flow. Based on the input of the parameters from various sensors opening and closing of the valves is decided. In the figure 2.1 a schematic of the original jig setup is shown. This comprises of a data acquisition system to input various parameters and output the controls accordingly.

2.1.1 Level sensor

Level sensor is a device which measures object distances through ultrasound waves. It is applied here to measure the water level in the jigging chamber. It is very sensitive device and a key component of the jigging operation. The model used here is a Senix make ULTRA U-SS 2 which connects with the data acquisition system to give the water level as a voltage signal. The sensor was re-calibrated using the serial port of the computer with the software given by the company to our requirement. It gave a uniform voltage from 5V to 0V corresponding to a distance from 16 cm to 76.2 cm. The decreasing voltage signal with distance was set deliberately so that in case of failure of the sensor or its power supply, 0V signal will correspond to a high water level and the valve on the other side of the U-tube will close connecting air chamber to the atmosphere. The maximum and minimum range suited our requirement. The calibration was checked with DAQ and the voltage output of the sensor was found to be linear with the distance.

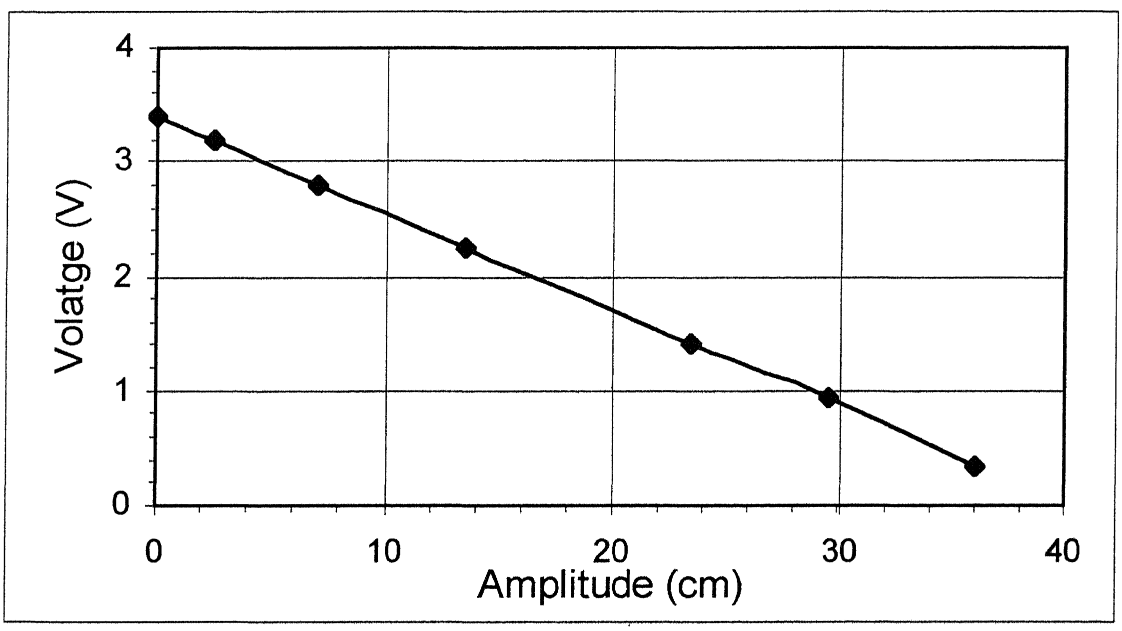


Figure 2.2 Calibration of the level sensor and its decreasing voltage signal with increasing distance.

2.1.2 Pressure Transducers

There are two places where the determination of air pressure is a must. The first is the compensator chamber, pressure of which serves as a parameter. The experiments can be repeated again and again keeping this parameter a constant. The second is the pressure in the air chamber (part of the U-tube). The determination of the pressure in U-tube serves many purposes. It can be used to know the lags present in the system if this pressure is plotted with the amplitude, velocity and compensator pressure. Secondly it can be used in a mathematical model for the process as a key parameter. The two pressure transducers are denoted by PT_1 and PT_2.

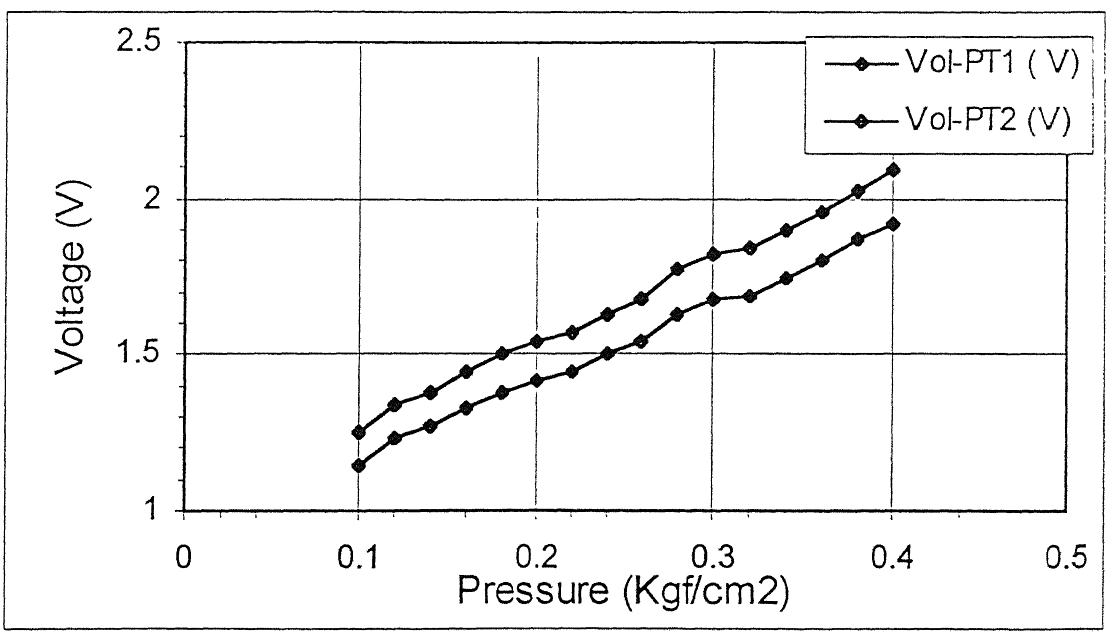


Figure 2.3 Variation of the pressure transducers outputs with pressure

The output of the pressure transducers is in mA. The range for these transducers is 0-1 Kg/cm^2. The current signal corresponding to this range is 4-20 mA. This is converted to a voltage signal with suitable resistance. PT_1 is calibrated with the help of a pressure indicator dial (<u>in static conditions</u>). PT_2 is also calibrated in the same way exchanging

with PT_1. It should be mentioned here that PT_1 and PT_2 gave the same output in terms of current. But because of slightly different resistances the voltage output is slightly different. The resistance used in PT_1 is 211 Ω and that in PT_2 is 194 Ω. The formula used for pressures are

$$p_1 = 0.3636\,(V_1 - 1.00)$$

$$p_2 = 0.3955(V_2 - 0.92)$$

where p_1, p_2 are the pressures PT_1 and PT_2. Similar is the case for V_1 and V_2 which are the output voltages for the pressure transducers PT_1 and PT_2.

2.1.3 Nucleonic Density Gauge

The nucleonic density gauge uses a radioactive gamma ray source which has a half life of 63 years. The density is converted to a current signal. This signal is again converted to a voltage signal with the help of a resister. The density thus obtained is actually wet bulk density, i.e., the average of the density of particle and water. If the particles are of the same size, it can be assumed that the path traveled by gamma ray in water is the same at all heights. Thus wet bulk density can be converted into actual density.

The output of the nucleonic density gauge is in terms of current which is converted into a voltage signal with the help of suitable resister. The current is given by

$$I = I_o e^{-\mu.\rho.x} \tag{2.1}$$

where I is the current output and I_o is current falling on the x length of a material of density ρ and μ is a constant. With the help of a log circuit this current is made liner with respect to the density. Thus if the density of a material of length x is made twice, the current output becomes half after passing through the circuit. The system is calibrated with pure water. After this the current-voltage output will be specific density with respect to water.

2.1.4 Solenoid Valves

There are three on-off type of valves used here. The first one (which is referred to as *valve1* in the program), is a two-way valve operated by 220V AC. This connects the compressor with the pressure compensator chamber. To operate it through a computer a special relay circuit was used. This was necessary because the DAQ used here does not have a relay output, i.e., the current output is not sufficient to open a relay (250 mA in our case). Thus with this circuit 5V means inlet is connected to outlet and 0 V means inlet is closed. As soon as a 5V signal is given to the circuit the valve opens supplying air into the compensator chamber. The compensator chamber is a big reservoir of air that is used to ensure that each jigging cycle is operated at a constant pressure.

The second valve (referred as *valve2* in the program) is a three-way valve. A similar relay circuit is used here as for the two-way valve. It is also operated by 220 V AC. This valve connects the pressure compensator chamber to the air chamber. Denoting outlet to the air chamber of the U-tube, inlet to the compensator and exhaust to the atmosphere, the following applies to the operation of the valve:

5V => (Inlet → Outlet) & (Exhaust ↓)

0v => (Inlet ↓) & (Outlet → Exhaust)

Opening of this valve by a 5V output pushes the air into the air chamber because of the pressure difference. This in turn pushes the water which pulsate the particle bed in the other side of the U-tube. At 0V the valve allows the air to be drained to the atmosphere from the air chamber.

The third valve (*valve3*) is also a three-way valve. This is an added feature to the existing set up for improved operation. This valve connects the compensator to the jigging chamber. But this valve is operated by a 12V DC source. Since the DAQ cannot provide 1A current required operating the valve, an external source was used in combination with

the relay circuit referred earlier. However the operation of the valve at different applied voltages is same as before.

2.1.5 Data acquisition Card (DAQ)

Data acquisition card used in this set of experiments is a PCL-208 card of Dynalog Micro-Systems. It has 12-bit resolution for ADC (Analog to Digital Converter) which is more than sufficient for our purpose. A 12-bit resolution means that the voltage is converted into a 12-bit data. Thus the minimum voltage the card can resolve is $^{1}/_{4095}$ of the range (Maximum possible binary number using 12-bit is 4095). The voltage range for ADC is 0-5V. It has 16 digital outputs 4 of which are used to operate relays with special circuits. The digital outputs are 4.7V. As mentioned above the digital outputs are not relay outputs (capable of giving 200mA current). This is the reason special circuits are used to draw appropriate current and thus to operate relay switches. The card has 16 single-ended channels for analog input (CH0-CH15). In other words it can read 16 voltage signals but all the voltage signals should have a common ground. When this card is used in differential mode, one has only 8 channels. The mode is selected through a jumper setting in the card. In our case the card is used in the differential mode.

2.2 Analysis of the Old System

The system used previously to study jigging is shown in Figure 2.1. This is the simplest system, in which pressure is applied to the one arm of the U-tube (called air chamber) till a fixed amplitude is achieved. The program for this is given in the Appendix II. It is evident from figure 2.6 that the "up" cycle is because of the air pressure in the compensator and the "down" cycle is due to gravity only. The obvious flaw of this setup is lesser control over the frequency of jigging since there is no control over the behavior of water during down cycle. To illustrate this situation the following theoretical analysis is made.

2.2.1 Theoretical Model

Consider the jig cycle in three distinct parts :

(i) Water is going upwards and the three way valve connecting the compensator to the air chamber is open

(ii) Water is going upwards and the valve is closed

(iii) Water is going downwards and the valve is open to the atmosphere

To get the total time required for the water to complete one cycle (i.e. move upwards from rest through the jig bed and then come down wards to the rest position) it is required to sum the time elapsed during the three parts of the cycle. Let the time taken during these parts be t_1, t_2, and t_3.

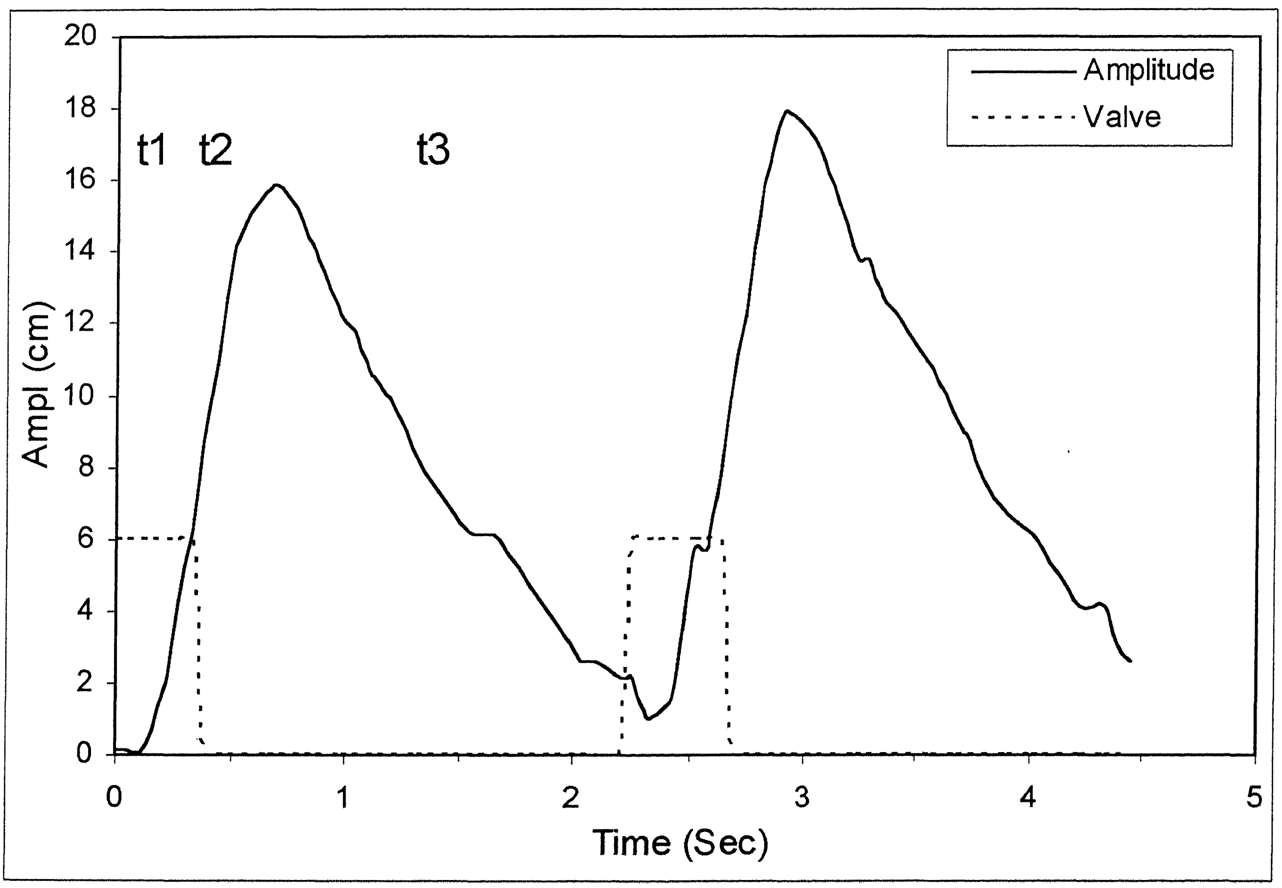


Figure 2.4 Variation of amplitude with time in the old jig setup

The pressure P in the compensator is almost constant because of the large capacity of the compensator. Also the extra pressure due to difference in water levels in the two columns can be neglected in the analysis of first part. The typical pressure is 20 kPa which is equivalent to 200 cm of water column. Thus neglecting the pressure due to difference in water levels during a jigging cycle is justified. Now applying the Newton's second law of motion to the first part the amplitude of water above the base plate x_1 can be calculated

$$x_1 = \frac{1}{2} \frac{PA}{(m_w + km_p)} t_1^{\,2} \tag{2.2}$$

From Eqn. 2.1 time elapsed in the first part can be calculated as

$$t_1 = \sqrt{\frac{2x_1 (m_w + km_p)}{PA}} \tag{2.3}$$

and

$$v_1 = \frac{PA}{(m_w + km_p)} t_1 \tag{2.4}$$

where v_1 is the velocity attained by the fluid during the first part of the cycle.

In the above equations k is a constant, the value of which depends on the fluid velocity and which varies between 0 and 1. If the particles move with the water with water's velocity the value of k would be 1. As we know that the velocity of the particles is less than that of the water the coefficient would be always be less than 1.

In the second part of the cycle although the valve is closed to the compensator the water is moving because of its momentum. The second and the third part, together, constitute part of an SHM. Let corresponding to that SHM t' be the time (of course fictitious) when the valve-2 is closed.

Thus,

$$x_1 = x.\sin(\omega.t') \tag{2.5}$$

and the velocity after time t' will be

$$v_1 = x.\omega.\cos(\omega.t') = \frac{PA}{(m_w + km_p)} t \tag{2.6}$$

This implies

$$\frac{\tan(\omega.t')}{\omega} = \frac{x_1(m_w + km_p)}{PAt_1} \tag{2.7}$$

Or,

$$t' = \frac{1}{\omega}\tan^{-1}\left(\frac{\omega x_1(m_w + km_p)}{PAt_1}\right) \tag{2.8}$$

where ω is angular frequency of the SHM. Putting the value of t_1 will give us the value of t'.

Also, t_3 is the time when water level comes from highest amplitude to the mid or base level.

Thus,

$$\omega(t' + t_2) = \frac{\pi}{2} = \omega.t_3 \tag{2.9}$$

Putting the value of t' in the above equations we can get the values of t_2 and t_3.

Total time during one cycle,

$$T = t_1 + t_2 + t_3 \tag{2.10}$$

$$T = \frac{\pi}{\omega} - \frac{1}{\omega}\tan^{-1}\left(\omega.\sqrt{\frac{x_1(m_w + km_p)}{2PA}}\right) + \sqrt{\frac{2x_1(m_w + km_p)}{PA}} \tag{2.11}$$

Here $k.m_p$ can be neglected in comparision with m_w.

Now ω for this kind of an SHM will be given by,

$$\omega = \sqrt{\frac{2g}{l}} \tag{2.12}$$

Now putting the value of ω, $m_w = l.A.\rho$ and taking the approximation tan x = x when x is small, we get

$$\boxed{T = \pi\sqrt{\frac{l}{2g}} + \sqrt{\frac{x_1 l \rho}{2P}}} \tag{2.13}$$

Now the frequency,

$$n = (1/T).60 \text{ cycles/min} \tag{2.14}$$

Three conclusions can be drawn from this :

(i) One can vary either the frequency or the amplitude of the motion with this kind of a setup, but not both.

(ii) The first term in determination of T is a constant and second term varies with pressure and x_1. Thus by varying pressure and x_1, one can change the frequency. But if we look the second term close enough we will realize that it is orders of magnitude lesser than the second term and thus change in frequency by changing the amplitude will be insignificant.

(iii) Because of a constant term in the equation of T, there will be an upper limit to which frequency can be increased.

2.2.2 Experimental Results:

To validate the above theoretical analysis a series of experiments were carried out. All the experiments were conducted with a bed height of 15 cm of mono-size particles of diameter around 1 cm and density 3100 Kg/m^3. Total length of water in the tube was kept fixed at 1.68 m. The results of the experiments are summarized in Table 2.1.

Table 2.1 Effect of pressure on amplitude and frequency in the old jig setup

S.N.	Amplitude (cm)	x_1 (cm)	Pressure (kPa)	Freq (cycles/min)
1	22	4	60	24
2	20	5	43	23
3	13	2	43	29
4	21	10	34	27
5	19	8	34	29
6	17	6	34	31
7	14	4	34	35
8	20	10	25	22
9	18	8	25	27
11	13	4	25	30
12	18	15	11.5	20
13	13	10	11.5	24

The range of frequencies obtained varies from 22 to 35. This is a limited range with higher and lower range difficult to achieve. It is obvious that there is a correlation between the amplitude and frequency. Increasing the pressure decreases t_1 but it gives a higher impulse to the water as a result of which t_3 is increased. Actually there is an optimum pressure at which the frequency will be the maximum. The table supports the theoretical deduction that there will be an upper limit above which the frequency cannot be increased.

2.3 Analysis of the Old System with Timer Control

The inherent drawback with the system with respect to attainable frequency was attempted to overcome in a different way. The control of the operation was done by using a timer in the software. This timer triggered the opening and closing of the valve at fixed time intervals. Earlier the level sensor was controlling the opening and closing of the valve. The obvious problem with the timer control was the fact that most of the times the triggering level did not correspond with the base level. This was a hazard as water level kept rising with each cycle. On the contrary if the water level is allowed to go back to the base level with suitable timer that it will be the same as previous experiments with some suitable amplitude.

The timer control was tested with several experiments. A typical result of the implementation is shown in figure 2.6. In this figure valve is open for a time period of 0.5 second and is then closed for 1.5 second. This figure was arrived at after hits and trials but it can be seen in the graph that the amplitude is decreasing though slowly. The reverse can also happen when the amplitude increases after each cycle.

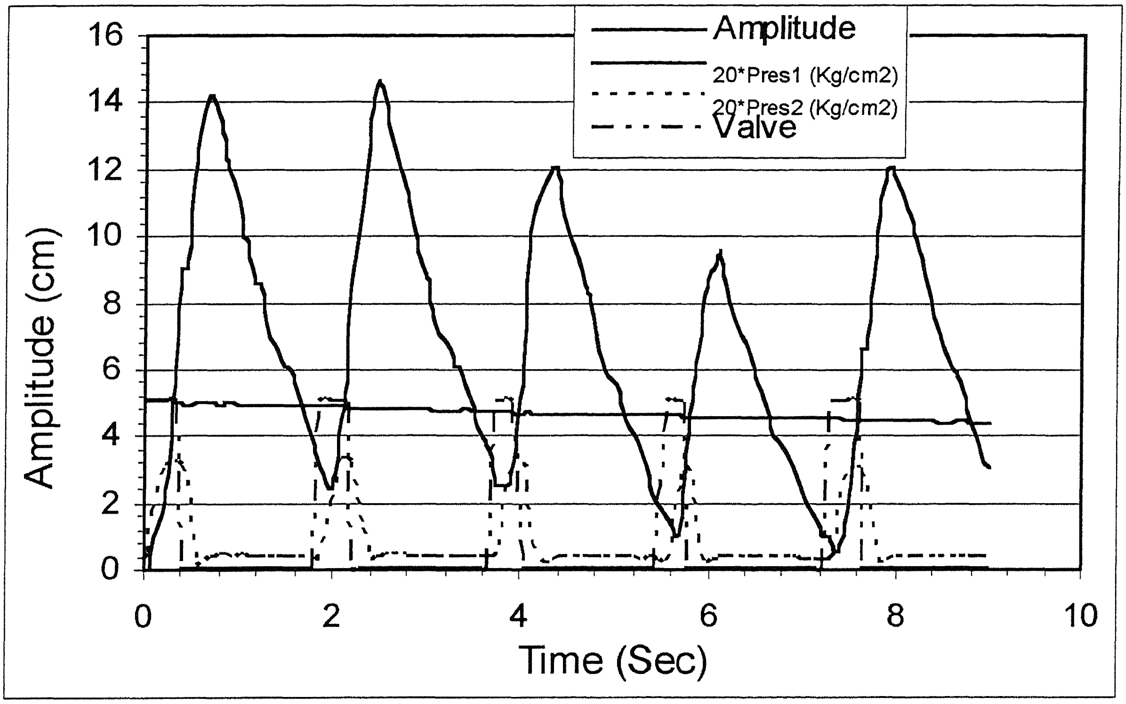


Figure 1.5 Timer control of valve in a jigging operation.

This kind of a control has following problems:

(i) It is based on hits and trials and thus the result of one system cannot be applied to the other system. Even if a minor modification is done in the system the values will change and new values will have to be obtained.

(ii) This is not an effective control. Though frequency can be fixed by hits and trials, the amplitude and the base level will keep changing.

(iii) No theoretical model can be developed for this kind of a control as it is based on hits and trials. And if a model is developed it will be of no practical use. Actually if in the down cycle also air pressure is given, the timer control will be more effective.

2.4 Analysis of the Old System with Back-Pressure of Water

To improve the range of amplitudes and frequencies and also to break the correlation between them (as shown in the previous chapter), a novel method was implemented. As it was obvious from the earlier experiments that the main bottleneck in increasing the frequency was the "down" cycle, in which the movement of the water column was entirely due to gravity. To decrease the time t_2 and t_3, backpressure was given with water column only. The water level was increased in one of the arms with the bed and this was the base level at which jigging was done.

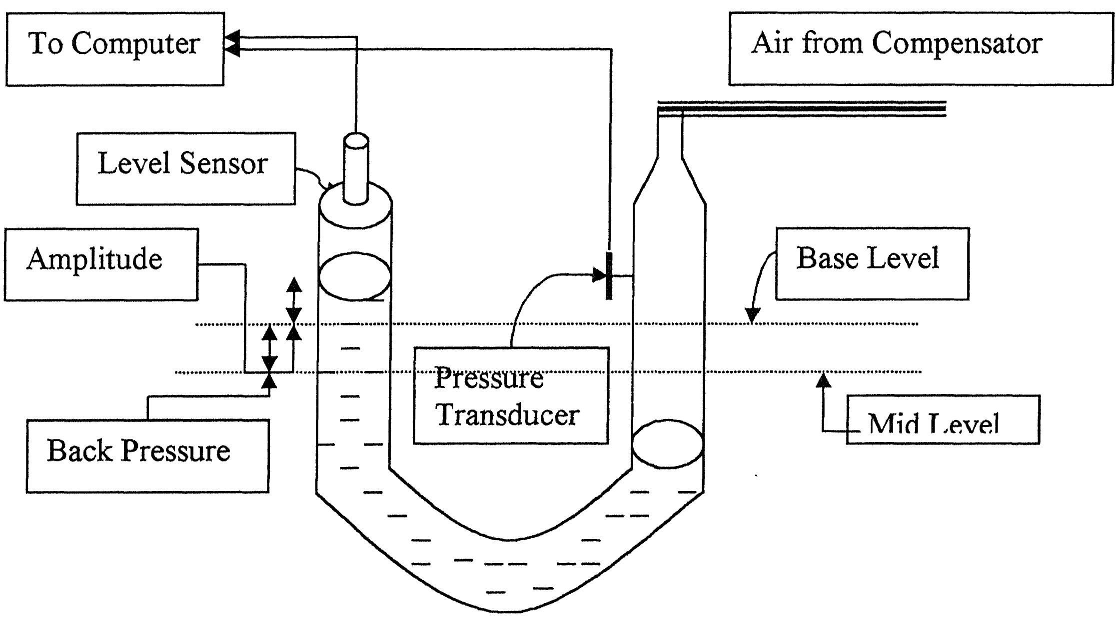


Figure 2.6 Schematic of the U-tube with various controls

The water level decreased the pressure in the "up" cycle only marginally but increased the pressure in down cycle considerably.

2.4.1 Theoretical Model

Following the lines of earlier analysis the cycle again can be divided into three parts with time spans t_1, t_2 and t_3.

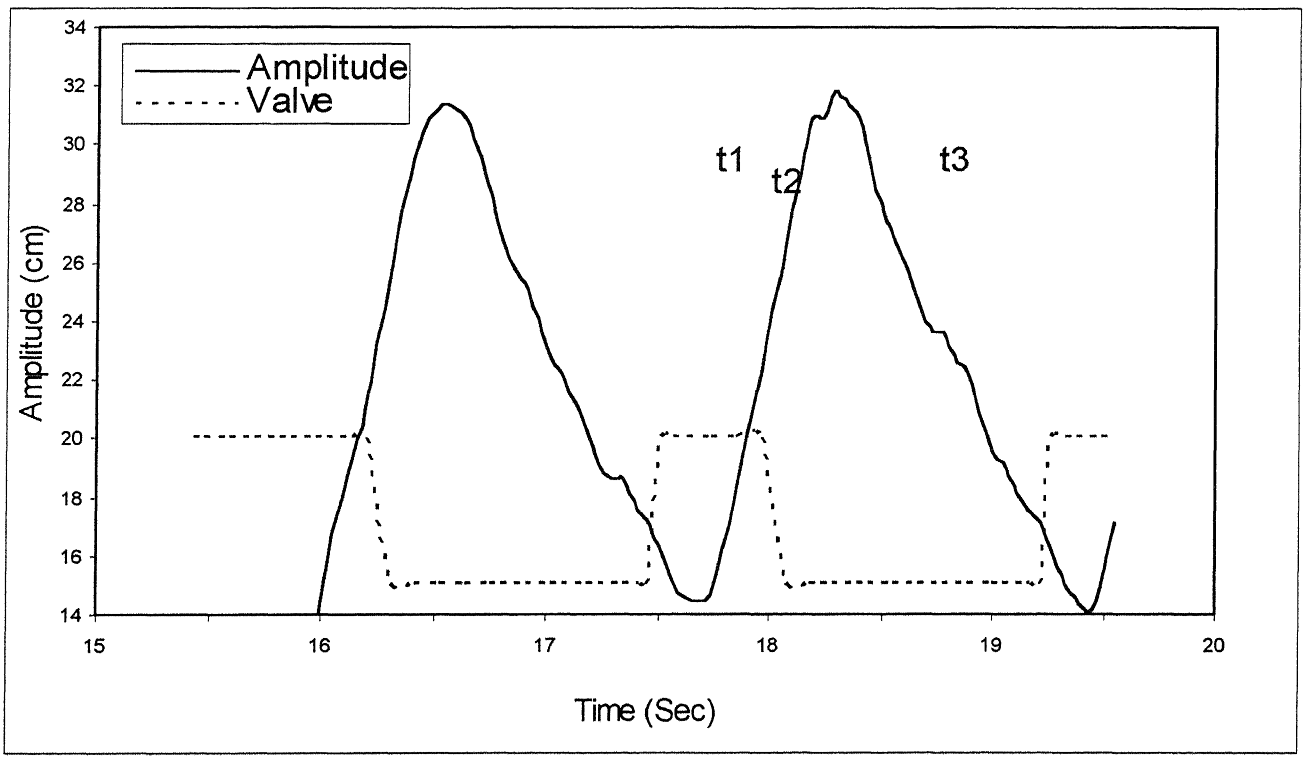


Figure 2.7 Plot of amplitude during back-pressure controlled jigging operation

$$x_1 = \frac{1}{2}\frac{(PA - 2\rho.gx_b A)}{(m_w + km_p)} t_1^{\ 2} \qquad (2.15)$$

This implies,

$$t_1 = \sqrt{\frac{2x_1(m_w + km_p)}{(PA - 2\rho.gx_bA)}} \tag{2.16}$$

Now the velocity after time t_1 will be

$$v_1 = \frac{(PA - 2\rho.gx_bA)}{(m_w + km_p)} t_1 \tag{2.17}$$

v_1 as in previous analysis is the velocity at the level x_1, when the valve 2 is closed. Neglecting $k.m_p$ in comparison with m_w, the equations 2.15, 2.16 and 2.17 reduces to

$$x_1 = \frac{1}{2}\frac{(PA - 2\rho.gx_bA)}{m_w} t_1^{\ 2} \tag{2.18}$$

$$t_1 = \sqrt{\frac{2x_1m_w}{(PA - 2\rho.gx_bA)}} \tag{2.19}$$

And,

$$v_1 = \frac{(PA - 2\rho.gx_bA)}{m_w} t_1 \tag{2.20}$$

The motion during time spans t_2 and t_3 can again be considered parts of an SHM. Thus,

$$(x_1 + x_b) = (x + x_b).\sin(\omega.t') \tag{2.21}$$

and

$$v_1 = (x + x_b)\omega.\cos(\omega.t') \tag{2.22}$$

Also

$$\omega.(t' + t_2) = \frac{\pi}{2} \tag{2.23}$$

And

$$x_b = (x + x_b).\sin(\omega.(t' + t_2 + t_3)) \quad (2.24)$$

Solving the above equations, we get

$$\frac{1}{\omega}\tan(\omega.t') = \frac{(x_1 + x_b)m_w}{(P - 2\rho.g.x_b)A.t_1} \quad (2.25)$$

This is indeed very complicated but still this can be simplified by taking two approximations :

(i) tan x $\approx$ x as x $\rightarrow$0 , which means

$$t' = \frac{(x_1 + x_b)m_w}{(P - 2\rho.g.x_b)A.t_1} \quad (2.26)$$

(ii) and $x_1 << x_b$

$$\frac{\sin(\omega.t')}{\sin\,\omega(t' + t_2 + t_3)} \approx 1 \quad (2.27)$$

Equation 2.27 implies

$$\omega(t' + t_2 + t_3) = \pi - \omega.t' \quad (2.28)$$

Or,

$$t_2 + t_3 = \frac{\pi}{\omega} - 2t' \quad (2.29)$$

Equations 2.19, 2.26 and 2.29 together give

$$T = t_1 + t_2 + t_3 = \frac{\pi}{\omega} + \sqrt{\frac{2x_1.m_w}{(PA - 2\rho.gx_bA)}} - \sqrt{\frac{(x_1 + x_b)^2 m_w}{2x_1(P - 2\rho.g.x_b)A}} \quad (2.30)$$

Above is the complete equation for time period of a cycle with back pressure of water

On putting $x_b = 0$, the equation 2.30 reduces to the one derived in earlier chapter.

Since $x_b > x_1$, in normal jigging operations

$$\frac{(x_1 + x_b)^2}{2x_1} \geq 2x_1 \tag{2.31}$$

This implies that 3rd term in the right hand side of the equation 2.30 will always be greater than the second term. This means that actually there will be a lower limit below which frequency cannot be achieved. In the normal experiments with old jig system, there is an upper limit above which the frequency cannot be obtained. Strange enough, the upper limit of the frequency in a normal experiment is the same as the lower limit of a experiment with backpressure of water. This means that now we have a range of frequencies to operate with. This range is from 20 to 50 cycles/min. With the current setup using the backpressure the frequency cannot be increased beyond 50 because of insufficient length of the U tube. Furthermore increasing frequency beyond this can be a hazard if the experiment is not performed carefully.

2.4.2 Experimental Results :

Figure 2.8 shows the variation of amplitude, pressure in the compensator (pres1), pressure in the air chamber (pres2) and condition of the valve (open/close) with time in a typical experiment. The experiment is performed continuously for 5 cycles and then valve 1 is opened to put the air pressure in the compensator at a desired level. This is done automatically to ensure that each jigging cycle is identical. The experiments are performed with a particle bed in the jigging chamber and not with water only. This dummy particle bed ensures that when the experiments are performed with real material the effect the mass of the particle bed is taken care of.

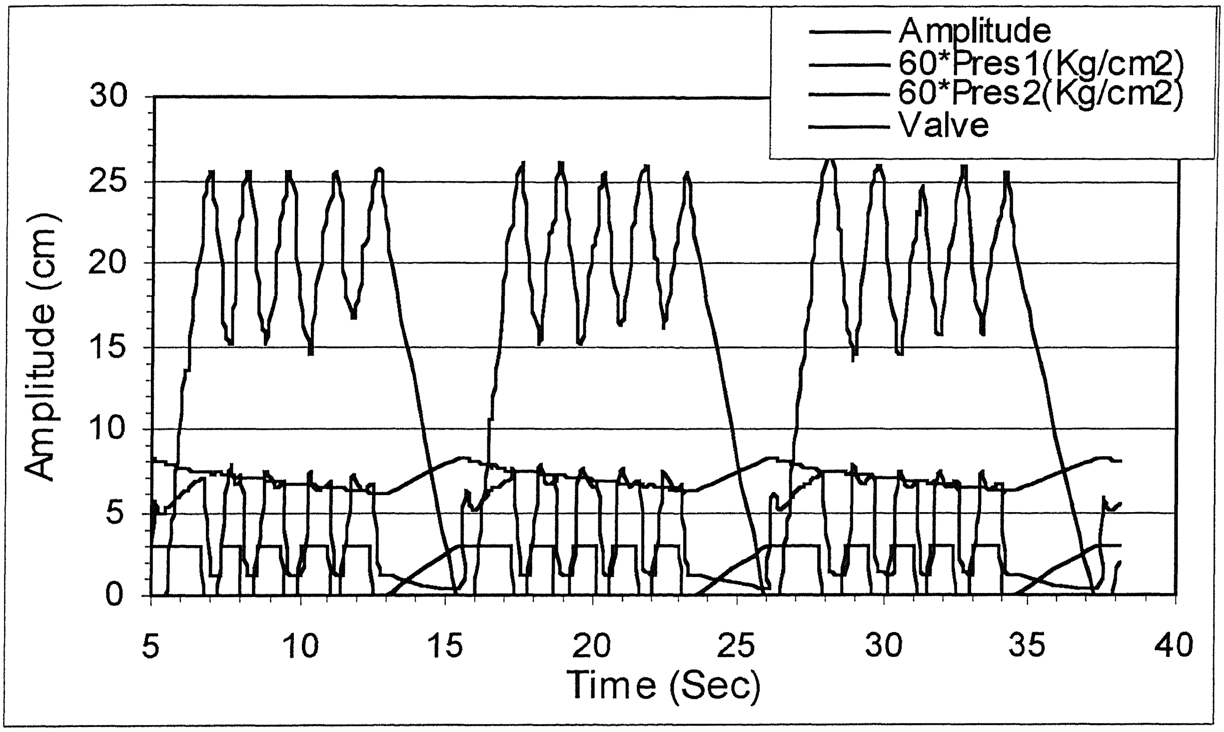


Figure 2.8 Variation of water level during jigging with back-pressure of water

The result of the experiments performed with the back-pressure of water is shown in the table 2.2. The conclusions of the above experiments can be summarized as :

(i) One can obtained, high range of frequencies, using back pressure of water.

(ii) There seems to be a lower limit below which the frequencies cannot be obtained. This is around 30-35 cycles/min. This is consistent with the theory that there should be a lower limit on the frequency.

(iii)The higher frequency is obtained at low pressure. This is because, with the same x_1, low pressure corresponds to low amplitude (x).

Table 2.2 Effects of various parameters during a jigging with back pressure of water

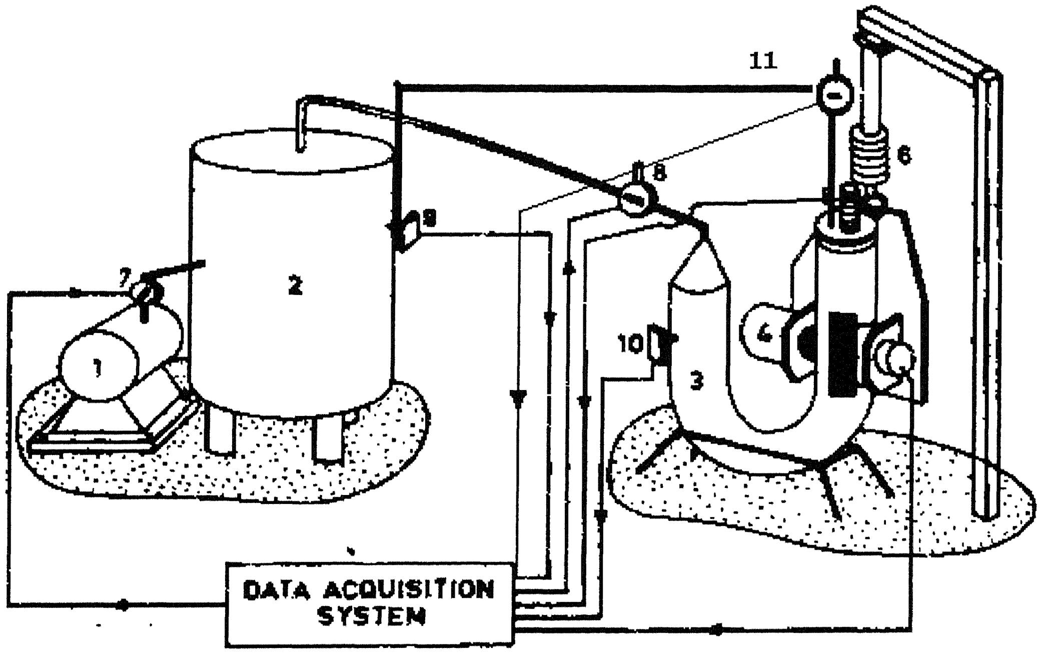
SN	Pressure (kPa)	x_1 (cm)	x_b (cm)	Amplitude (cm)	Frequency (cycles/min)
1	34	3	20	16	41
2	34	3	15	16	36
3	34	2	20	14	41
4	25	5	15	15	39
5	25	3	20	10	41
6	25	3	15	12	46
7	16	5	10	12	38
8	16	3	20	9	50
9	11.5	3	20	9	45

But this kind of a system has one drawback. Higher frequencies corresponds to low pressure and amplitude which means low water velocity and impulse to the bed. Thus the higher frequencies obtained this way will not stratify the bed as desired.

2.5 Analysis of the New System

To overcome the limitations in the system with back-pressure of water and to obtained higher range of frequency, it was decided to connect the compensator with the jigging chamber. This proved useful as the down cycle could also be controlled with an extra 3-way valve (referred as valve3 in the program). The schematic of the new system is shown in the figure 2.7. The air chamber is connected to the compensator through valve2 in the up cycle and the jigging chamber is connected to the compensator in the down cycle.

This increased the range of frequencies. Frequencies of 80-85 cycles/min have also be obtained in the experiments.



1. Compressor 2. Compensator 3. Jig 4. Nucleonic density gauge 5. Level sensor
6. Pneumatic Actuator 7. Two-way solenoid valve 8. Three-way solenoid valve
9. and 10. Pressure transducers 11. Three way solenoid valve

Figure 2.9 The new jig system with an extra 3-way solenoid valve

Two controls namely amplitude controlled jigging and timer controlled jigging were tried to this setup. Of the two controls tried timer control proved to be more effective than the amplitude control. At high frequency the vibration are very high. The outlet of valve3 and the level sensor are connected to the same plate. This caused the level sensor to vibrate and give erroneous valves though rarely. The amplitude control was not desirable because even a single erroneous value will cause the valves to switch their states (ON/OFF). A timer control in this case is more reliable. The very high and very low values corresponding to <0.5V and >4.5V were filtered because the normal voltage range is 2-3.5 V. The only problem with this control was deciding the time spans in which valve2 and valve3 are open. This was done by hits and trials. Ideally the time spans

should be the same for both three-way valves but because of various lags in the system they are slightly different.

2.5.1 Experimental data

Table 2.3 Effect of various parameters on frequency and amplitude in the new jig setup

SN	Pressure (kPa)	Up Time (Sec)	Down Time (Sec)	Amplitude (cm)	Frequency (cycles/min)
1	18	0.35	0.45	5	70
2	25	0.4	0.4	10	70
3	37	0.4	0.4	15	70
4	11	0.45	0.50	5	60
5	16	0.5	0.5	10	60
6	25	0.5	0.5	15	60
7	7.3	0.55	0.65	5	50
8	11	0.55	0.65	10	50
9	17.5	0.6	0.6	15	50
10	5.0	0.7	0.8	6	40
11	7.5	0.7	0.8	10	40
12	11.1	0.75	0.75	14	40

Table 2.3 shows the effectiveness of the new system. The experiments have been performed at various frequencies, though the data is collected for 40-70 cycles/min. With the new system experiment can be performed at any amplitude and frequency in the given range. There is no correlation between the amplitude and the frequency as in earlier jig setup.

The uptime and the downtime are equal at moderate and high pressure. This is expected also because the air chamber and the jigging chamber are connected with the same compensator. This causes the same pressure in the air and jigging chambers when the respective valves are open.

Downtime is slightly higher than uptime at low pressure. This might be because of the fact that from the valve3 to the jigging chamber there is a ½" pipe whereas from valve2 to air chamber there is 1" pipe. Thus the flow rate in the jigging chamber is slightly lower.

Chapter 3

CRITICAL VELOCITY FOR FLUIDIZATION

With the new jig system one can have a range of frequencies and amplitudes to operate the jig. One can make a fairly large number of combinations of amplitude and frequency. Nonetheless, not all the combinations of frequency and amplitude are useful. Some combinations may not even fluidize the bed, let alone stratification. Therefore it becomes imperative to know those combinations of amplitude and frequency that will make the system work. In order to achieve this objective the theory of interaction between particle and the fluid was considered from first principle. This involved interaction of drag, buoyancy and gravity forces for a particle bed. The bed behavior can be derived by considering all the forces acting on a single particle. While the buoyancy and the gravity forces remain constant, the drag force on a particle in a fluid actually depends upon the relative velocity of the particle and the fluid. It is expected that the bed will fluidize when all the forces due to the interaction with the fluid for all the particles add up to negate the effect of their total weight. At this point there should be a critical velocity of the fluid at which the particle bed will fluidize.

The aim of the present chapter is to understand how particles stratify in a pulsating fluid medium and also to get the critical velocity at which the fluidization will start. For this a mathematical model is developed based on simple fluid mechanics principles. This mathematical model is then used to predict the minimum fluidization velocity for a given particulate system which in turn is compared with experimental observations.

3.1 The Model

When a particle moves in a pulsating fluid medium it experience drag, buoyancy, and the gravity force. However, many researchers (Srinivasan et. al. [6], Beck and Holtham) have considered an added mass to the particles in a jigging process. If a particle is moving in a fluid, some of the fluid mass gets attached to the particle and moves with the particle. But in their analysis they have taken a constant added mass that cannot be justified. In fact the boundary layer thickness changes with the relative velocity of the particle and thus the added mass keeps on changing. In each cycle of the jig there is a definite variation in the velocity of the particle that cannot be ignored. In the present analysis added fluid mass is not considered explicitly. However, by taking a proper correlation for the friction coefficient the added mass can be accommodated in the force balance equation.

In the present analysis all the particles are considered to be of the same diameter but different densities. This can only approximate the actual process but it gives a good qualitative understanding of the process. Also the same analysis can be extended for particles of different diameter and densities.

A macroscopic view is taken in the analysis. In other words, instead of doing the analysis at the particle level, here the analysis is aimed at the entire particle assembly. The example of the Kinetic Theory of Gases can be taken to make the point clear. One can analyze the interaction of two gases in a closed chamber by molecular dynamics methods given enough computing power. But it is not worth that much of computational effort when one seeks overall change in behavior of the system. Moreover the model developed will be very particular and cannot be generalized where the local effects may turn out to be difficult to understand and analyze. Even a small variation of the parameters like shape, size, etc., will make the matter more complicated. Given the large size of the population a macroscopic model can be developed. Reducing the problem in small elements and adding them to get the result has its own limitations. This is what is done in microscopic analysis. In the macroscopic view one can safely ignore local variation which will average out to be zero and one can arrive at a more appropriate average property.

3.2 Mathematical Analysis

At the critical velocity all the particles are either moving or in dynamic equilibrium under the influence of various forces. It is assumed that there are n_1 particles of density ρ_1, n_2 particles of density ρ_2 and so on. There are in all n particles of k types. All the particles are of the same radius r. The surface properties of all the particles is assumed to be the same. It means that if two particles of different densities are moving with the same velocity they will undergo the same drag force.

Without loss of generality we can assume that $\rho_1 < \rho_2 < \rho_3 \ldots < \rho_{k-1} < \rho_k$. It is obvious that if the equilibrium is achieved for the heaviest particle, all other particles will be moving. Increasing the velocity above this will fluidize the bed that may eventually lead to stratification of the bed. Thus the critical velocity is a velocity at which the heaviest particle is in equilibrium and the drag force on it equals the force due to gravity and buoyancy.

The velocity, which is measured, is the velocity of the upper surface of the fluid. The velocity of the fluid in the voids cannot be measured directly but for the upper surface one can set an ultrasonic level sensor and measure the velocity very accurately. The drag is caused by the fluid in the space between the voids and the velocity of the fluid in the voids is much higher than that of the upper surface of the fluid.

To measure the velocity of the fluid in the voids we should measure the effective area available to fluid in between the bed. Letting the total volume of the particles as V_p and that of liquid between the voids as V_l, the total volume of the fluid in the void and the particles is

$$V = h.A = V_p + V_l \tag{3.1}$$

where, h is the height of the bed and A is the cross sectional area of the jig. The total volume of the liquid in voids is

$$V_l = V - V_p \tag{3.2}$$

Now the effective cross sectional area available to the fluid

$$A_{eff} = \frac{V_l}{h} \tag{3.3}$$

Putting the value of V_l gives

$$A_{eff} = A - \frac{V_p}{h} \tag{3.4}$$

One can then apply the continuity equation to get the velocity of the fluid in the voids as

$$A_{eff} . v_{eff} = A . v \tag{3.5}$$

where v is the velocity of the fluid surface and v_{eff} is its velocity in the voids. This means

$$v_{eff} = A . v / A_{eff} \tag{3.6}$$

After putting the value of A_{eff} from Eqn. (3.1) v_{eff} becomes

$$v_{eff} = \frac{v}{1 - \frac{v_p}{h.A}} \tag{3.7}$$

This implies,

$$\boxed{v_{eff} = \frac{v}{\varepsilon}} \tag{3.8}$$

where ε is the volume fraction of the voids in particle bed. The minimum value which ε can have is the same as in close packed system of spheres, i.e., 0.26. In the above equation all parameters except v_{eff} are measurable. Thus one can estimate the effective velocity of the fluid in the voids which is generating drag on the particles that in turn are fluidized.

It can be shown, that the flow in the voids will be turbulent (See Appendix I). Stoke's Law cannot be applied in the present case. For the viscous drag, various correlations can be used and the equation may become

$$F_d = C_D \frac{\rho_k v_{eff}^{\;2}}{2} A_p \tag{3.9}$$

where ρ_k is the density of the heaviest particle, A_p is cross sectional area of that particle and C_D is a constant, which depends on Reynold Number. Putting the value of v_{eff} in the equation

$$F_d = C_D \frac{\rho_k\, v^2}{2\varepsilon^2} A_p \tag{3.10}$$

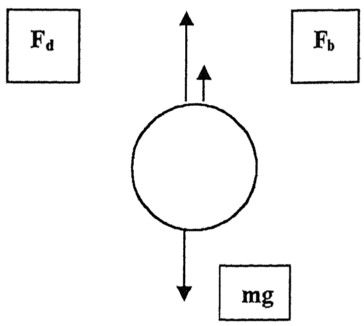


Figure 3.1 Forces acting on a particle due to the presence of a fluid.

For critical velocity, this drag force will be just balanced by the gravity and buoyancy as shown in figure 3.1.

$$F_d = mg - F_b \tag{3.11}$$

This implies,

$$F_d = \frac{4}{3}\pi . r^3(\rho_k - \rho)g \tag{3.12}$$

Putting the value of F_d from Eqn. 3.5 and taking $A_p = \pi r^2$, yields

$$C_D \frac{\rho_k v_{cri}^2}{2\varepsilon^2} = \frac{4}{3\rho_k}(\rho_k - \rho) r\ g \tag{3.13}$$

which when simplified becomes

$$\boxed{v_{cri}^2 = \frac{8rg}{3C_D \rho_k}(\rho_k - \rho)\varepsilon^2} \tag{3.14}$$

As shown by Felice [11] in the presence of other particles C_D will be given by

$$C_D = \varepsilon^{-3.7}(0.63 + \frac{4.8}{\sqrt{R_e}})^2 \tag{3.15}$$

Putting the value of C_D in the equation and taking $g = 9.81$

$$\boxed{v_{cri} = \frac{8.1.\varepsilon^{2.85}}{(1 + \frac{7.62}{\sqrt{R_e}})}\sqrt{r(1 - \frac{\rho}{\rho_k})}} \tag{3.16}$$

This is the complete equation but it can be simplified by several assumptions. It has been shown (See Appendix I) that the Reynolds number will be very high in case of jigging. This allows $(1 + \frac{7.62}{\sqrt{R_e}})$ to become equal to 1. Also, in the beginning of fluidization ε can be taken as that of a loose packing, say, 0.47. Thus it can be shown that

$$\boxed{v_{cri} = 0.98\sqrt{r(1 - \frac{\rho}{\rho_k})}} \tag{3.17}$$

Above is a very simple result and following conclusions can be drawn qualitatively:

- Critical velocity increases with the radius of the particles and is zero when the radius is zero.
- Critical velocity increases with the increase in density and is zero when the density of all the particles is equal to that of the fluid.

3.3 Experimental validation

To put this equation to a quantitative test two cases were taken using two types of particles. These were of the same size. The experiment was performed at low pressure to test the limit of fluidization. Five jig cycles are given to the particle bed. Since the pressure reduces with each cycle, one can get a situation when the particle bed fluidizes in first few cycles and does not fluidize in last few cycles.

Taking the first case for r = 1cm, $\rho = 1.0$ g/cm^3, $\rho_k = 3.1$ g/cm^3, v_{cri} was determined to be 8 cm/sec. The bed in this case moved in the first two cycles and in the third cycles just the upper layer moved. In the fourth and fifth cycle the bed did not move at all. The amplitude of pulsation (level of water above a fixed height) achieved is shown in figure 3.2.

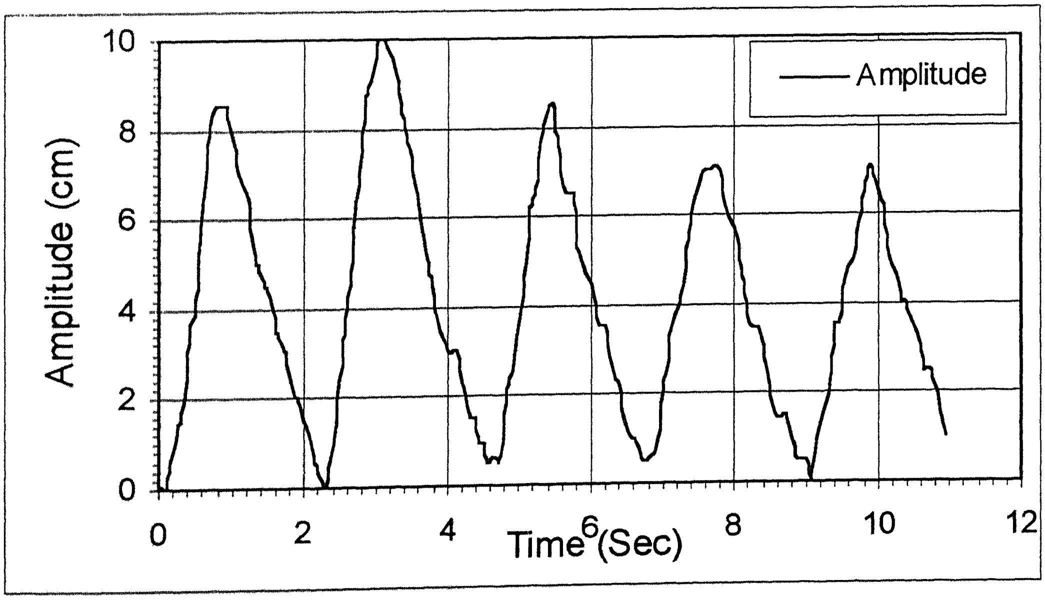


Figure 3.2 Variation of amplitude and velocity with time for $\rho_k = 3.1$ g/cm^3

Now, for the second case for r = 1cm, ρ = 1.0 g/cm^3 and ρ_k = 2.65 g/cm^3 v_{cri} was determined to be 6 cm/sec. The bed in this case moved in the first three cycles and in the last two cycles bed did not move at all. The amplitude of pulsation attained is shown in figure 3.3.

To calculate the velocity one way would be to take the ratio of the differences of amplitudes at different times for consecutive data points. But this produced noises in the velocity profile. To overcome this the average velocity during "up" motion was calculated. For this highest and lowest points were taken for each cycles. The result is summarized in the table 3.1

Table 3.1 Measured values of critical velocity

Number of Cycles	Velocity (cm/s) for ρ_k = 3.1 gm/cc	Velocity (cm/s) for ρ_k = 2.65 gm/cc
1	12.3 Bed moved	12.14 Bed moved
2	12.5 Bed moved	12.8 Bed moved
3	12.14 Bed moved	11.5 Bed moved
4	8.12 Bed did not move	7.5 Bed did not move
5	8.2 Bed did not move	7.1 Bed did not move

For the first bed the experimental data goes very well with the theory. The theoretical value is 8 cm/sec whereas the experiment gives a value higher than 8 but less than 12 cm/sec. While carrying out the experiment it was noticed that for the first three cycles the bed pulsated considerably. Therefore it is believed that the critical velocity is close to 8 than 12 cm/sec.

For the second bed of particles involving glass balls the critical value obtained is higher than that predicted by the theory which is between 7.5 and 11.5 cm/sec. Here again noticeable movement of the bed was observed for a velocity of 11.5 cm/sec. Thus, as before, the critical velocity is assumed to be more close to 7.5 cm/se. This value is also quite close to the theoretical value of 6 cm/sec. The discrepancy may be because of the fact that in the second bed the particles used were glass balls, which had a very smooth surface. This is expected to reduce the drag causing the critical velocity to increase.

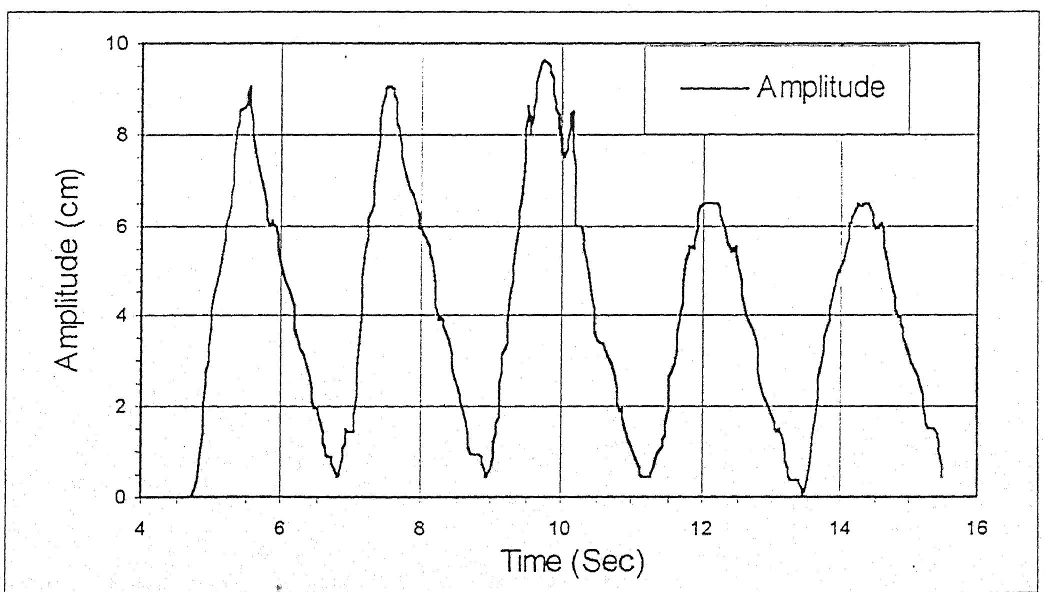


Figure 3.3 Variation of amplitude with time for $\rho_k = 2650$ Kg/m^3

3.4 Reverse Segregation

Equation 3.17 predicts that with increasing density or diameter of a particle the critical velocity will increase. A condition may occur where particles of higher density are of lower size than the particles of lower density in such a way that the critical velocity for particles of lower density is higher than that for particles of higher density. If the velocity is increased any further there will be reverse segregation and the particles of higher density will be above the particles of lower density. The equation 3.17 can also be used to derive the condition of reverse segregation.

The critical condition for reverse segregation will be the condition when the critical velocities for both type of particles are the same. Thus equating the critical velocity one can get a relation which will show the boundaries of reverse segregation.

Chapter 4

EXPERIMENTS WITH BINARY SYSTEM OF PARTICLES

The control of the jig was designed and tested successfully as described in earlier chapters. With this a wide range of frequency and amplitude was available. Once a jig is available in which experiments can be performed with wide range of frequencies and amplitudes, the next work is to test the combinations of frequencies and amplitudes most suited for stratifications. In others words, if two types of particles with different densities are taken, what combination of these parameters helps to widen the CG (Center of Gravity) difference of the two types of particles. With selected combinations of frequencies and amplitudes many experiments were done to see the actual stratification of the particle bed.

4.1 Experimental Setup

Two types of particles were chosen, namely zirconia and glass. Zirconia has a density of 3100 Kg/m^3 while glass has a density of 2650 Kg/m^3. These two types of particles were roughly of the same size, i.e. 1 cm. Thus all the particles taken were similar in size. The combinations of frequency and amplitude were chosen in such a way that the entire range of frequency and amplitude possible with the present setup was covered.

Timer control was used in this. In timer control the opening and closing of the valves are done at fixed times as compared to fixed levels in the level controlled jigging. This gave a

very effective control over the frequency. The amplitude can be increased by either increasing the force (or pressure) or increasing the time for which the force is applied. Theoretically the *uptime* is should be equal to the *downtime* because both the jigging and air chamber are connected to the same compensator and thus the same pressure differential. This means for a fixed frequency the uptime will be fixed. Now the amplitude for this frequency can be increased by increasing the pressure.

4.2 Experimental Data

4.2.1 40 Cycles/min

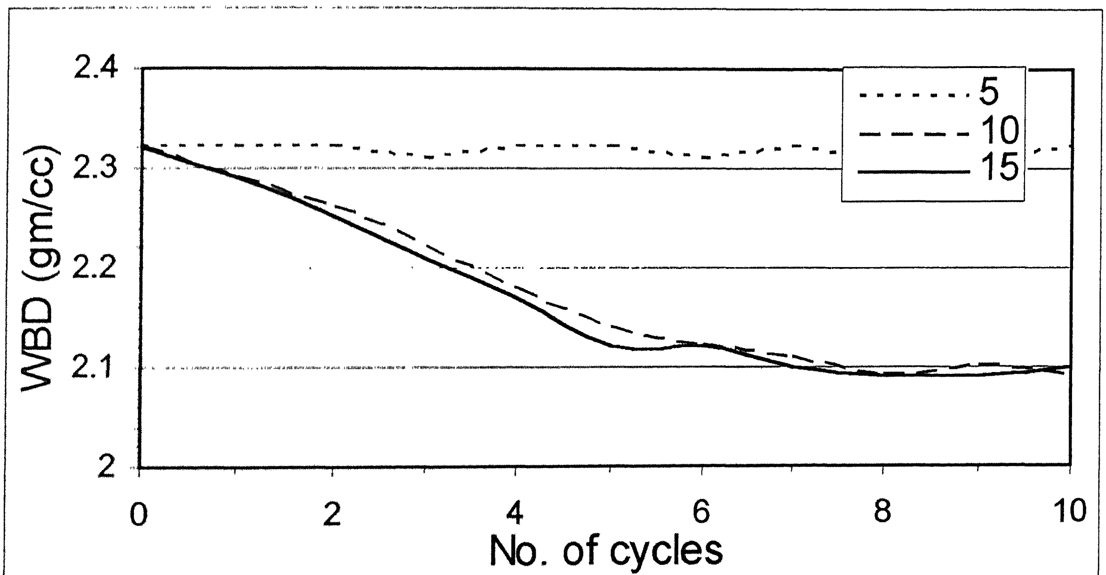


Figure 4.1 Variation of Wet Bulk Density at a frequency of 40 cycles/min

The variation of Wet Bulk Density at a frequency of 40 cycles/min is shown in the figure 4.1. At this frequency, an amplitude of 5 cm did not produce any stratification. The bed did not move at all in this case. If the average velocity during *uptime* motion is calculated
It should be less than the critical velocity needed to lift the particle bed. The average velocity during up motion can be calculated by taking the ratio of amplitude and uptime. This comes out to be around 7 cm/sec for a frequency of 40 cycles/min and amplitude 5 cm. As we know from the previous chapter that at this velocity even the lighter particles

(glass balls) will not move. Thus it is expected that this combination will not stratify the bed.

For amplitudes of 10 cm and 15 cm the stratification observed is almost the same. Though the stratification for an amplitude of 15 cm is marginally higher than that for 10 cm. But higher amplitude means more pressure which in turn imply more power consumed by the jig. Thus a compromise has to be made between the amplitude and stratification.

4.2.2 50 Cycles/min

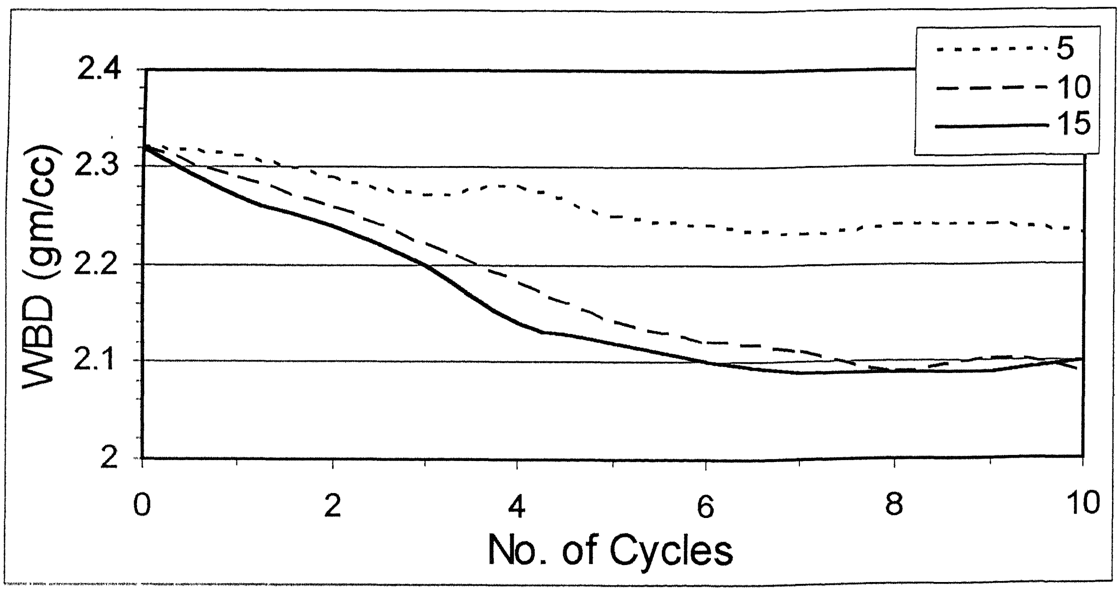


Figure 4.2 Variation of Wet Bulk Density at a frequency of 50 cycles/min

Figure 4.2 shows the variation of Wet Bulk Density for three different amplitudes at the frequency 50 cycles/min. At this frequency, if 5 cm amplitude is used, though the bed is stratified it is very slow. This might be because of the fact that the average velocity in the up motion is sufficient to lift the particle bed, but the bed does not expand sufficient enough to cause significant stratification. The amplitudes of 10 cm and 15 cm produce almost similar stratification in this case similar to the last case of a frequency of 40 cycles/min.

4.2.3 60 Cycles/min

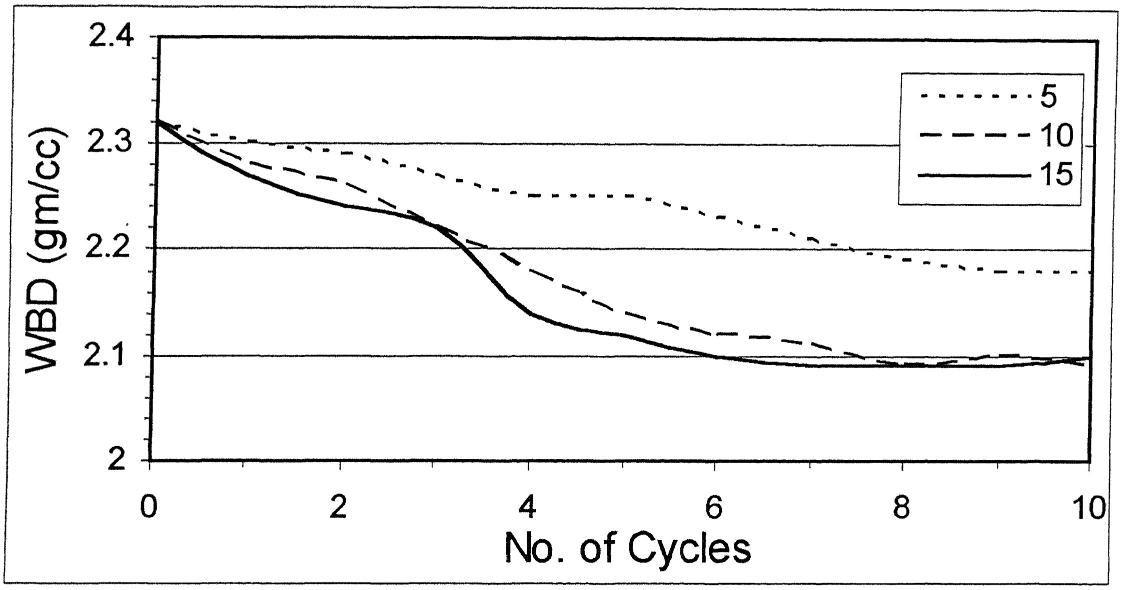


Figure 4.3 Variation of Wet Bulk Density at a frequency of 60 cycles/min

The above figure shows the Wet Bulk Density at three different amplitudes for a frequency of 60 cycles/min. At this frequency the amplitude of 5 cm produce very low stratification. This is because of the fact that though the fluid velocity is greater than the critical velocity the bed does not expand enough to give any room for stratification. However the amplitudes of 10 cm and 15 cm gives good stratification. Similar to previous experiments these amplitudes produce almost similar stratification.

4.2.4 70 Cycles/min

The figure 4.4 shows the stratification behavior at a frequency of 70 cycles/min. This frequency is supposed to be in higher range as for as jigging is concerned. Unexpectedly the amplitude of 5 cm did not produce any observable stratification. Though the average velocity seems The possible reason for this may be the fact that at this high frequency the whole bed is disturbed and the particles did not get sufficient time to settle.

The amplitude of 15 cm at this frequency gives poorer stratification as compared to 10 cm. While at lower frequencies the amplitude of 15 cm always gives marginally better stratification as compared to 10 cm. The reason again may be the fact that at this frequency the entire bed is disturbed if more than sufficient room is given to the particles to stratify. Thus at higher frequencies there is an optimum amplitude which produce best stratification.

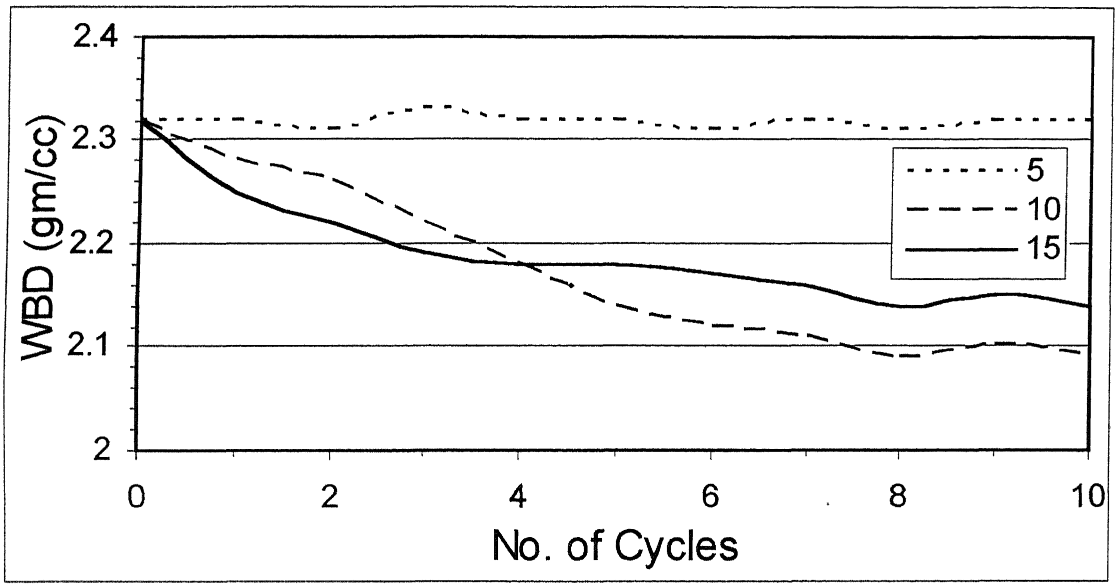


Figure 4.4 Variation of Wet Bulk Density at a frequency of 70 cycles/min

4.3 Comparison of various frequencies

The discussion will be incomplete if the effect of frequencies on the jigging is not discussed. For this the Wet Bulk Density is plotted for amplitudes of 15 cm and 10 cm in the figure 4.5 and 4.6 respectively.

At the amplitude of 15 cm the stratification increases as the frequency is increased from 40 cycles/min to 60 cycles/min. However the stratification is poor when the frequency is further increased to 70 cycles/min. At higher frequency the entire bed is disturbed and this result in poor stratification.

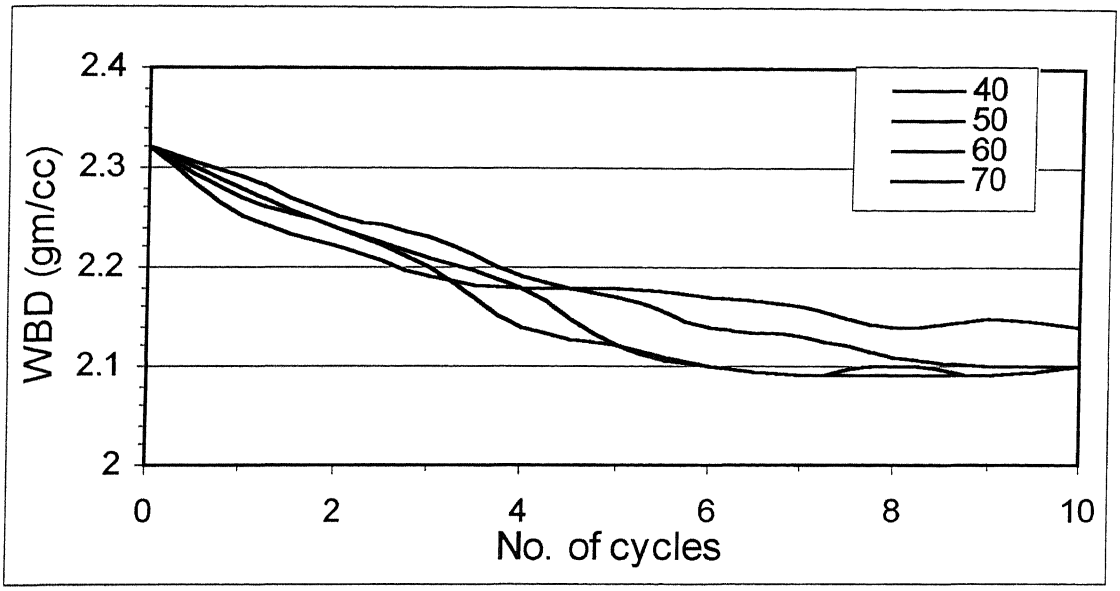


Figure 4.5 Variation of Wet Bulk Density at amplitude of 15 cm

At an amplitude of 10 cm the stratification increases as the frequency is increased. However the frequencies of 60 and 70 cycles/min produce similar stratification But if the curve is looked more closely it will be obvious that the frequency of 60 cycles/min gives better stratification as compared to that of 70 cycles/min.

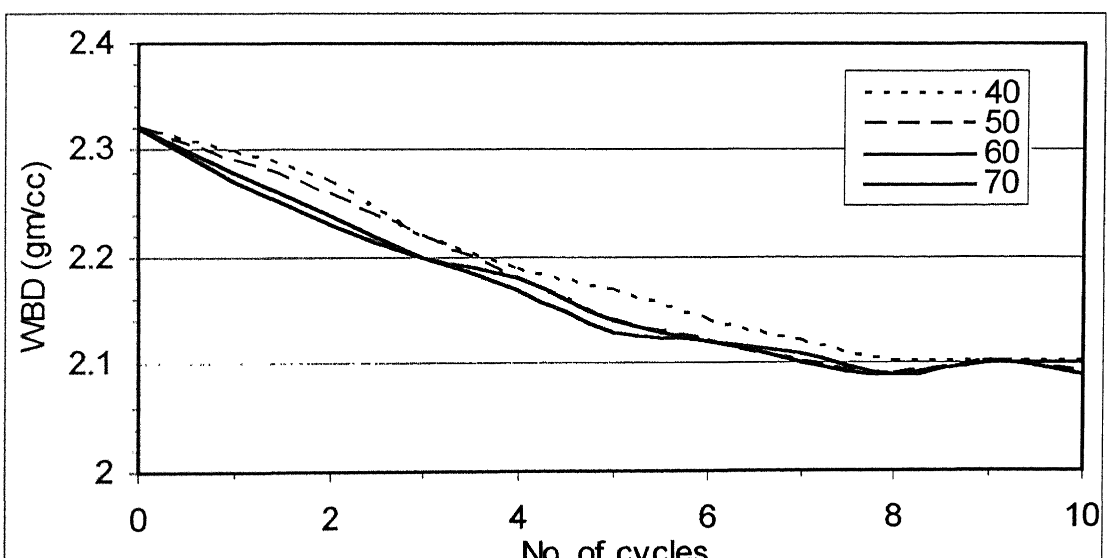


Figure 4.6 Variation of Wet Bulk Density at amplitude of 10 cm

4.3(A) Washing of Coal Using New Jig

Coal of size 2.8mm to 4mm was jigged using the new setup. Since the density of coal is low the critical velocity will also be low for these particles. The critical velocity for these particles will be around 4cm/sec as per the theoretical model. This means that the optimum frequency should also be lower for this kind of particles. A rough estimate puts the value of optimum frequency to be around 40 cycles/min. The jigging was done for 12 cycles and 24 cycles.

Ash content in the original sample was 35 %. The sample was jigged at 40 cycles/min. Samples were taken from the top and the bottom

Table 4-A Ash content in Coal Samples Taken from the Top and Bottom Layer

	12 cycles	24 cycles
Top Sample	26.3%	27.2%
Bottom sample	39.6%	38.0%

This shows that Indian coal can be washed provided the instrumentation and control is proper. If ash content can be reduced even by 2-3 %, this will mean a huge profit. Low ash content will also lead to less power consumption and problems of fly-ash disposal

4.4 Conclusions

Normally the stratification increases with increasing the frequency. But this happens at lower and mid frequencies only. At higher frequencies because of higher turbulence the stratification is comparatively poor.

The effect of amplitude on stratification is more complex. At low amplitudes either there is no stratification or there is poor stratification. This owes to the fact that there is very little room for the particle bed to expand. At higher amplitudes the effect of amplitude on the stratification is not very significant. This is because the bed requires a minimum expansion length to stratify. As this expansion length is achieved the effect of increasing expansion length (or amplitude) on the stratification behavior is reduced.

Chapter 5

RESULTS AND DISCUSSION

Before the present investigation started many experiments were done in jigging at IIT Kanpur with an instrumented batch jig. The setup of the old jig had several drawbacks. First, the range of frequency was limited to 28-30 cycles per minute. Second, the fluid waveform generated was highly irregular

To improve upon the system a new program was written with no reference to the earlier program. The time() function used was replaced with clock() function. This gave a better control over time of opening and closing of the valves that allows air to enter and exit from the air chamber. Pressure transducers, level sensor and nucleonic density gauge were recalibrated. Each parameter namely valve condition (open or close), pressure in air chamber, pressure in the compensator and the amplitude of the water was recorded into separate data files simultaneously for a given jigging cycles. This helped in better understanding of the process.

Several preliminary tests were carried out for a comprehensive system analysis. It was concluded from the analysis of the data recorded during each of those experiments that it was the "down" motion of the water that was consuming longer time compared to the "up" motion. Since the "down" motion takes place due to gravity only, there is no control over it. No significant change in the system would have been possible if the "down" motion was not checked. In other words the intention was to minimize the "down" motion time.

In order to reduce the "down" time two simple ideas were implemented. The first idea was to improve the down time by applying the backpressure of water during the down motion. This improved the frequency significantly. But due to the height of jigging chamber back pressure was limited and thus frequency was limited to around 50 cycles/min. Further because of high water level there was always a danger of water going into the level sensor if proper attention is not paid. Nevertheless this was almost 50 percent improvement over the past practice.

A further improvement in the system was made by connecting the jigging chamber with the compensator. Thus both the jigging chamber as well as the air chamber (two arms of the U-tube), were connected with the compensator through two three-way valves. Thus the water was pushed back by the air during the down cycle. This reduced the downtime significantly. Because of the reduced downtime a higher frequency was now possible. Thus a range of 20 to 80 cycles/min could be covered with the new system as compared to 20 to 35 from the old system.

A theoretical model was developed for critical velocity at which the particle bed will fluidize. The value of this critical velocity is then compared with the experimental data. The theoretical velocity closely matches with the experimental results. Thus beforehand it can be predicted what combination of frequency and amplitude will stratify the bed.

Many experimental were performed at different amplitudes and frequencies with a binary system of particles. This helped in understanding the effect of frequency and amplitude on the overall stratification behavior. It was established that there exists an optimum frequency at which the stratification is achieved in least number of jig cycles. Finally some experiments were done with coal particles of size around 4mm. It was established that the jigging can reduce ash content considerably.

Future Work and Scope of Improvement

The density gauge signal, the pulse velocity signal, and a dynamic model of bed fluidization can be used to derive an on-line measurement of stratification which can be used to quickly configure a jig for optimal control. Combined with information from the stratification model, this activity will hopefully be realized in 2-3 years if this research activity is carried forward.

The instruments have been used to highlight common problems and features of jig operation and control which otherwise must be deduced by trial and error. The proven ability to directly measure pulsation velocities and density gradients in jig beds is expected to provide the kind of detailed information required by researchers, jig manufacturers, and jig users alike to promote jigs as a cost effective, reliable, and well understood unit operation.

Appendix

I

Determination of fluid flow in jigging

Let us suppose that the flow is laminar and we can apply stoke relation to compute the drag.

$$\Rightarrow \quad F_d = 6\pi\eta r v_{eff}$$

Where η is the viscosity of the fluid and r is it's radius. In equilibrium it should balance gravity and buoyancy.

$$\Rightarrow 6\pi\eta r v_{eff} = \frac{4}{3}\pi r^3 (\rho_k - \rho) g$$

Where ρ_k is the density of the particle and ρ is the density of the fluid.

$$\Rightarrow v_{eff} = \frac{2}{9}\frac{r^2(\rho_k - \rho)g}{\eta}$$

Now Reynolds Number

This D, should be taken as the diameter of the tube and not the diameter of the particle.

$$R_e = \frac{\rho v_{eff} D}{\eta}$$

$$\Rightarrow R_e = \frac{2\rho(\rho_k - \rho) r^2 g v D}{9\eta^2 (1-\varepsilon)}$$

In a typical case of jigging :

$\eta = 10^{-3}$ MKS Unit

$\rho_k = 3000$ Kg/m^3

$\rho = 1000\ Kg/m^3$

$g = 10\ m/sec^2$

$r = 0.01\ m$

$D = 0.15\ m$

$\varepsilon = 0.47$

$\Rightarrow R_e = 2.0 \times 10^7$

In engineering applications the threshold for turbulent flow is taken as 2300, though laminar flow can be observed at Reynold number as high as 40,000. But in the present case it is orders of magnitude higher than the threshold limit. Thus the flow of the fluid past the particles will be essentially turbulent.

II

Modified Jig program for the old Jig

```
/* '*********************************************************************
   '* Program  : Jig.c                          *
   '* Version : 2.0                             *
   '* Date    : 14/03/02                         *
   '* Coded by : Vineet Kumar Dwivedi                      *
   '* Under the Guidance of : Dr. B. K. Mishra              *
   '*********************************************************************/

//This program take the input of pt1,pt2, sensor only
//Motion is controlled through height of water
//Improvement of old jig program with Safety features and etc....

#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <share.h>
#include <conio.h>
#include <math.h>
#include <time.h>
#define clk_per_sec 1000.00F


void readdata(),output(),delay(float tim),initialize();
void openvalve(int valve_id),closevalve(int valve_id);
void checkpress();;
float gettime(),readport(int ch_id),convert(float pres);
void jig();
int start_ch, stop_ch, r_ch,ch_val;
```

```
// Global Variables
float ampl,pres,density,time0,time1,time_start,time_stop;
int n;
int port = 0x300;    //Initialize Base Address
FILE *fp,*ft;
float vol,vol_cri,HIGH,LOW;
char keyb;

void main()
{
  initialize();
  printf("Zig 1.1 Software by Vineet Kr. Dwivedi\n");
  readdata();
  fp=fopen("Data.xls","w");
        time0=gettime();

     time_start= gettime();

     jig(); //JIG THE BED 'N' TIMES

     time_stop= gettime();

     output(); //PRINT THE DETAILS AFTER JIGGING

     printf ("ENTER [e]EXIT OR ANOTHER CONVERSION\n");

  fclose(fp);
}

void readdata()   // TAKE THE INPUT PARAMETERS
   {
    printf("\nInput the pressure in Kg/cm2  ");
    scanf("%f",&pres);
            if (pres>=0.8) {   //Safety Feature
```

```
printf("This is very HIGH Pressure\nI am exitting...\n");
exit(0);
}
vol_cri=convert(pres);
printf("\nInput the amplitude in cm   ");
scanf("%f",&ampl);
if (ampl>=20) {   //Safety Feature
printf("This is very HIGH Amplitude\nI am exitting...\n");
exit(0);
}

printf("\nInput No. of times you want me to jig   ");
scanf("%d",&n);
printf("Pressure1=%f voltage = %f \n",pres,vol_cri);
printf("No. of cycles = %d \n",n);
}
float convert(float pres) //Give the voltage corresponding to Pr in Kg/cm2
{
return (pres*(2.5)+0.95);
}


void output()
{

printf("Time taken for %d cycles = %f seconds\n",n,(time_stop-time_start));
printf("Average frequency = %f cycles per min\n",60*n/(time_stop-time_start));

}
```



```
void checkpress()
{
```

```
  openvalve(1);

  do
    {
     delay(0.05F);
     vol = readport(0);
    }
  while(vol<=vol_cri);

            printf("vol_cri   = %f   vol  =  %f\n",vol_cri,vol);
  closevalve(1);
  if(vol>=(1.1*vol_cri))
        {
    printf("WARNING: COMPENSATOR PRESSURE IS TOO HIGH\n");
     printf("Open the manually operated Valve for air exhaust ");
     exit(0);

  }
 }

float readport(int ch_id)
 {
  int st,dth,dtl,adl,adt;

     ch_val=ch_id*16+ch_id;    /* SET SCAN CHANNEL VALUE */
 _outp(port+2,ch_val);
 r_ch=_inp(port+2);    /* READ BACK CHANNEL VALUE */
 if (r_ch != ch_val)
 {
   printf ("set scan channel failed!\n");
   exit(0);
 }
```

```
        _outp(port,0);
        do
          st = _inp(port+8);
        while ((st & 0x80) == 0x80);
        dtl  = _inp(port);
        dth = _inp(port+1);
        adl = dtl/16;
        adt = dth*16 + adl;
        ch_val =dtl-adl*16;
        if (ch_val == ch_id)
        return(adt*(5.0F/4096.0F));

  }



void jig()
  {
   int i,j;
   float timecheck,level,level0,height,high,low,time,press1,press2;
   level0=readport(1);
            if (level0<=0.5) exit(0);  //Safety Feature
            low=level0-0.084*ampl;
   high=level0-0.2;
            printf("\n%.2f\t%.2f\n",high,low);
            n=n/5;
            printf("%d\n",n);
            for (j=1;j<=n;j++){
                checkpress();  //CHECK THE COMPENSATOR PRESSURE
            for (i=1;i<=5;i++){
                openvalve(2);
```



```
                do {
                      press1=0.3636*(readport(0)-1);
```

```
                    press2=0.3955*(readport(2)-0.92);
                    level=readport(1);
                    time=gettime()-time_start;
                    fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t%.2f\n",time,((level0-
level)/0.084),20*press1,20*press2,ampl);
                    delay(0.05);
                }while(level>low);

                    closevalve(2);

        do {
                    press1=0.3636*(readport(0)-1);
                    press2=0.3955*(readport(2)-0.92);
                    level=readport(1);
                    time=gettime()-time_start;
                    fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t0\n",time,((level0-
level)/0.084),20*press1,20*press2);
                    delay(0.05);
                }while(level<high);

        }}
  }

void openvalve(int valve_id)

   {
    if (valve_id ==1)
      {
       _outp(port+4,0xff);
       _outp(port+5,0xff);
       printf("VALVE 1 OPENED\n");
```

```
      }
    if (valve_id == 2)
      {
```

```
            _outp(port+6,0xff);
            _outp(port+7,0xff);
            printf("VALVE 2 OPENED\n");
          }
       }

 void closevalve(int valve_id)
      {
       if (valve_id == 1)
         {
          _outp(port+4,0x00);
          _outp(port+5,0x00);
          printf("VALVE 1 CLOSED\n");
         }
      if (valve_id == 2)
         {
         _outp(port+6,0x00);
         _outp(port+7,0x00);
         printf("VALVE 2 CLOSED\n");
         }
     }

float gettime()
     {
      clock_t clockNo;

      clockNo=clock();
      return clockNo/clk_per_sec;
     }

void delay(float tim)
   {
    clock_t clock0,clock1;
    clock0=clock();
```

```
    time0=clock0/clk_per_sec;
    do
    {
    clock1=clock();
    time1=clock1/clk_per_sec;
    }while((time1-time0)<=tim);
  }

void initialize()     //INITIALIZE THE CARD AND I/O PORTS
  {
  int c_reg,r_ch;
  int ch_val,val,st;
      int uni_pol,diff_inp;

  printf("Hardware verification ..............\n");



  val=0x70;
  _outp( port+9,val);
  c_reg=_inp(port+9);
        if (c_reg != val)
    {
    printf ("pcl-718 hardware verification failed!\n");
    exit(0);
    }
  _outp(port+8,1);     //CLEAR INTERRUPT REQUEST

  // READ A/D STATUS REGISTER
 uni_pol=0;
 diff_inp=0;
 st=_inp(port+8);
  if ((st & 0x40) == 0x40)
    uni_pol=1;
  if ((st & 0x20)!=0x20)
```

```
     diff_inp = 1;
   }

   if (diff_inp==0)
      printf("Total 16 channels \n");
     else
      printf("Total 8 differential channels\n");

   if (uni_pol==0)
     printf("Bipolar Input \n");
    else
     printf("Unipolar Input\n");


start_ch=1;
      stop_ch=1;
 ch_val=stop_ch*16+start_ch;     /* SET SCAN CHANNEL VALUE */
_outp(port+2,ch_val);
r_ch=_inp(port+2);      /* READ BACK CHANNEL VALUE */
if (r_ch != ch_val)
{
   printf ("set scan channel failed!\n");
   exit(0);
}
            printf ("\nSTART SCAN CHANNEL= %d",start_ch);
   printf ("\nSTOP SCAN CHANNEL= %d\n",stop_ch);

             // INITIALIZE ANALOG OUTPUT PORTS
              _outp(port+4,0x00);
    _outp(port+5,0x00);
    _outp(port+6,0x00);
    _outp(port+7,0x00);
}
```

III

Program to give back pressure of water during down cycle in the old jig

```
/* '**********************************************************************
   '* Program  : Jig5.c                          *
   '* Version : 2.0                             *
   '* Date    : 15/03/02                         *
   '* Coded by : Vineet Kumar Dwivedi                    *
   '* Under the Guidance of : Dr. B. K. Mishra             *
   '**********************************************************************/

/This program take the input of pt1,pt2, sensor only
//Motion is controlled through height of water
//High Frequency is with back pressure of water

#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <share.h>
#include <conio.h>
#include <math.h>
#include <time.h>
#define clk_per_sec 1000.00F


void readdata(),output(),delay(float tim),initialize();
void openvalve(int valve_id),closevalve(int valve_id);
void checkpress();;
float gettime(),readport(int ch_id),convert(float pres);
```

```
void jig();
int start_ch, stop_ch, r_ch,ch_val;
// Global Variables
```

```
float ampl,pres,density,time0,time1,time_start,time_stop,back_pressure;
int n;
int port = 0x300;    //Initialize Base Address
FILE *fp,*ft;
float vol,vol_cri,HIGH,LOW;
char keyb;

void main()
{
  initialize();
  printf("Zig 1.1 Software by Vineet Kr. Dwivedi\n");
  readdata();
  fp=fopen("Data.xls","w");
        time0=gettime();

      time_start= gettime();

      jig();  //JIG THE BED 'N' TIMES

      time_stop= gettime();

      output();  //PRINT THE DETAILS AFTER JIGGING

      fclose(fp);
}

void readdata()   // TAKE THE INPUT PARAMETERS
    {
     printf("\nInput the pressure in Kg/cm2   ");
     scanf("%f",&pres);
               if (pres>=0.8) {   //Safety Feature
                         printf("This is very HIGH Pressure\nI am exitting...\n");
                         exit(0);
               }
```

```
                vol_cri=convert(pres);
                printf("\nInput the amplitude in cm   ");
        scanf("%f",&ampl);
                if (ampl>=20) {   //Safety Feature
                        printf("This is very HIGH Amplitude\nI am exitting...\n");
                        exit(0);
                }

                printf("\nInput the Back Pressure Amplitude in cm   ");
        scanf("%f",&back_pressure);

                printf("\nInput No. of times you want me to jig   ");
        scanf("%d",&n);
        printf("Pressure1=%f voltage = %f \n",pres,vol_cri);
        printf("No. of cycles = %d \n",n);
    }
 float convert(float pres)  //Give the voltage corresponding to Pr in Kg/cm2
 {
 return (pres*(2.5)+0.95);
 }


void output()
    {

        printf("Time taken for  %d  cycles =   %f   seconds\n",n,(time_stop-time_start));
        printf("Average  frequency  =  %f   cycles per min\n",60*n/(time_stop-time_start));

    }
```



```
void checkpress()
    {
```

```
      openvalve(1);

      do
        {
         delay(0.05F);
         vol = readport(0);
        }
      while(vol<=vol_cri);

                printf("vol_cri   = %f   vol  = %f\n",vol_cri,vol);
     closevalve(1);
     if(vol>=(1.1*vol_cri))
           {
         printf("WARNING: COMPENSATOR PRESSURE IS TOO HIGH\n");
          printf("Open the manually operated Valve for air exhaust ");
          exit(0);

      }
    }

float readport(int ch_id)
  {
   int st,dth,dtl,adl,adt;

        ch_val=ch_id*16+ch_id;    /* SET SCAN CHANNEL VALUE */
  _outp(port+2,ch_val);
  r_ch=_inp(port+2);     /* READ BACK CHANNEL VALUE */
  if (r_ch != ch_val)
  {
    printf ("set scan channel failed!\n");
    exit(0);
  }
```

```
        _outp(port,0);
        do
          st = _inp(port+8);
        while ((st & 0x80) == 0x80);
        dtl  = _inp(port);
        dth = _inp(port+1);
        adl = dtl/16;
        adt = dth*16 + adl;
        ch_val =dtl-adl*16;
        if (ch_val == ch_id)
        return(adt*(5.0F/4096.0F));

   }



void jig()
    {
     int i,j;
     float timecheck,level,level0,height,high,low,time,press1,press2;
     level0=readport(1);
               if (level0<=0.5) exit(0);  //Safety Feature
               low=level0-0.084*(ampl+back_pressure);
     high=level0-0.084*back_pressure-0.1;
               printf("\n%.2f\t%.2f\n",high,low);
               n=n/5;
               printf("%d\n",n);
               for (j=1;j<=n;j++){
                      checkpress();  //CHECK THE COMPENSATOR PRESSURE
               for (i=1;i<=5;i++){
                      openvalve(2);
```



```
                      do {
                             press1=0.3636*(readport(0)-1);
```

```
                                press2=0.3955*(readport(2)-0.92);
                                level=readport(1);
                                time=gettime()-time_start;
                                fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t%.2f\n",time,((level0-
level)/0.084),20*press1,20*press2,ampl);
                                delay(0.05);
                        }while(level>low);

                                closevalve(2);

                do {
                                press1=0.3636*(readport(0)-1);
                                press2=0.3955*(readport(2)-0.92);
                                level=readport(1);
                                time=gettime()-time_start;
                                fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t0\n",time,((level0-
level)/0.084),20*press1,20*press2);
                                delay(0.05);
                        }while(level<high);

                }}
    }

void openvalve(int valve_id)

    {
     if (valve_id ==1)
        {
         _outp(port+4,0xff);
         _outp(port+5,0xff);
         printf("VALVE 1 OPENED\n");
        }
     if (valve_id == 2)
        {
```

```
          _outp(port+6,0xff);
          _outp(port+7,0xff);
          printf("VALVE 2 OPENED\n");
        }
     }

 void closevalve(int valve_id)
    {
     if (valve_id == 1)
       {
        _outp(port+4,0x00);
        _outp(port+5,0x00);
        printf("VALVE 1 CLOSED\n");
       }
     if (valve_id == 2)
       {
       _outp(port+6,0x00);
       _outp(port+7,0x00);
       printf("VALVE 2 CLOSED\n");
       }
    }

float gettime()
   {
    clock_t clockNo;

    clockNo=clock();
    return clockNo/clk_per_sec;
   }

void delay(float tim)
  {
   clock_t clock0,clock1;
   clock0=clock();
```

```
    time0=clock0/clk_per_sec;
    do
    {
    clock1=clock();
    time1=clock1/clk_per_sec;
    }while((time1-time0)<=tim);
  }

void initialize()     //INITIALIZE THE CARD AND I/O PORTS
  {
  int c_reg,r_ch;
  int ch_val,val,st;
       int uni_pol,diff_inp;

  printf("Hardware verification ...............\n");



  val=0x70;
  _outp( port+9,val);
  c_reg=_inp(port+9);
         if (c_reg != val)
    {
    printf ("pcl-718 hardware verification failed!\n");
    exit(0);
    }
  _outp(port+8,1);     //CLEAR INTERRUPT REQUEST

  // READ A/D STATUS REGISTER
 uni_pol=0;
 diff_inp=0;
 st=_inp(port+8);
```



```
  if ((st & 0x40) == 0x40)
    uni_pol=1;
  if ((st & 0x20)!=0x20)
```

```
diff_inp = 1;
}

if (diff_inp==0)
  printf("Total 16 channels \n");
 else
  printf("Total 8 differential channels\n");

if (uni_pol==0)
 printf("Bipolar Input \n");
else
 printf("Unipolar Input\n");


start_ch=1;
      stop_ch=1;
 ch_val=stop_ch*16+start_ch;    /* SET SCAN CHANNEL VALUE */
_outp(port+2,ch_val);
r_ch=_inp(port+2);    /* READ BACK CHANNEL VALUE */
if (r_ch != ch_val)
{
   printf ("set scan channel failed!\n");
   exit(0);
}
            printf ("\nSTART SCAN CHANNEL= %d",start_ch);
   printf ("\nSTOP SCAN CHANNEL= %d\n",stop_ch);

            // INITIALIZE ANALOG OUTPUT PORTS
             _outp(port+4,0x00);
    _outp(port+5,0x00);
    _outp(port+6,0x00);
    _outp(port+7,0x00);
}
```

IV

Level controlled jigging operation with new jig

```
/* '***********************************************************************
   '* Program  : Jig2.c                              *
   '* Version : 2.0                                 *
   '* Date     : 14/03/02                            *
   '* Coded by : Vineet Kumar Dwivedi                          *
   '* Under the Guidance of : Dr. B. K. Mishra                  *
   '***********************************************************************/
//This program take the input of pt1,pt2, sensor only
//Motion is controlled through height of water
//Improvement of Zig2 with Safety features and etc....

#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <share.h>
#include <conio.h>
#include <math.h>
#include <time.h>
#define clk_per_sec 1000.00F


void readdata(),output(),delay(float tim),initialize();
void openvalve(int valve_id),closevalve(int valve_id);
void checkpress();;
float gettime(),readport(int ch_id),convert(float pres);
void jig();
int start_ch, stop_ch, r_ch,ch_val;
// Global Variables
```

```
float ampl,pres,density,time0,time1,time_start,time_stop;
int n;
int port = 0x300;     //Initialize Base Address
FILE *fp,*ft;
float vol,vol_cri,HIGH,LOW;
char keyb;

void main()
{
  initialize();
  printf("Zig 1.1 Software by Vineet Kr. Dwivedi\n");
  readdata();
  fp=fopen("Data.xls","w");
        time0=gettime();

      time_start= gettime();

      jig();  //JIG THE BED 'N' TIMES

      time_stop= gettime();

      output();  //PRINT THE DETAILS AFTER JIGGING

      printf ("ENTER [e]EXIT OR ANOTHER CONVERSION\n");

  fclose(fp);
}

void readdata()    // TAKE THE INPUT PARAMETERS
   {
    printf("\nInput the pressure in Kg/cm2  ");
    scanf("%f",&pres);
              if (pres>=0.8) {   //Safety Feature
                     printf("This is very HIGH Pressure\nI am exitting...\n");
```

```
                exit(0);
            }
            vol_cri=convert(pres);
            printf("\nInput the amplitude in cm   ");
    scanf("%f",&ampl);
            if (ampl>=20) {    //Safety Feature
                printf("This is very HIGH Amplitude\nI am exitting...\n");
                exit(0);
            }

            printf("\nInput No. of times you want me to jig   ");
    scanf("%d",&n);
    printf("Pressure1=%f voltage = %f \n",pres,vol_cri);
    printf("No. of cycles = %d \n",n);
  }
float convert(float pres) //Give the voltage corresponding to Pr in Kg/cm2
{
return (pres*(2.5)+0.95);
}


void output()
  {

    printf("Time taken for  %d  cycles =   %f   seconds\n",n,(time_stop-time_start));
    printf("Average  frequency  =  %f   cycles per min\n",60*n/(time_stop-time_start));

  }
```



```
void checkpress()
  {
```

```
    openvalve(1);

    do
      {
       delay(0.05F);
       vol = readport(0);
      }
    while(vol<=vol_cri);

            printf("vol_cri   = %f   vol  =  %f\n",vol_cri,vol);
    closevalve(1);
    if(vol>=(1.1*vol_cri))
          {
       printf("WARNING: COMPENSATOR PRESSURE IS TOO HIGH\n");
       printf("Open the manually operated Valve for air exhaust ");
       exit(0);

    }
   }

float readport(int ch_id)
  {
   int st,dth,dtl,adl,adt;

       ch_val=ch_id*16+ch_id;    /* SET SCAN CHANNEL VALUE */
  _outp(port+2,ch_val);
  r_ch=_inp(port+2);    /* READ BACK CHANNEL VALUE */
  if (r_ch != ch_val)
  {
    printf ("set scan channel failed!\n");
    exit(0);
  }

       outp(port,0);
```

```
         do
           st = _inp(port+8);
         while ((st & 0x80) == 0x80);
         dtl  = _inp(port);
         dth = _inp(port+1);
         adl = dtl/16;
         adt = dth*16 + adl;
         ch_val =dtl-adl*16;
         if (ch_val == ch_id)
          return(adt*(5.0F/4096.0F));

  }



void jig()
   {
    int i,j;
    float timecheck,level,level0,height,high,low,time,press1,press2;
    level0=readport(1);
              if (level0<=0.5) exit(0);  //Safety Feature
              low=level0-0.084*ampl;
    high=level0-0.2;
              printf("\n%.2f\t%.2f\n",high,low);
              n=n/5;
              printf("%d\n",n);
              for (j=1;j<=n;j++){
                     checkpress();  //CHECK THE COMPENSATOR PRESSURE
              for (i=1;i<=5;i++){
                     openvalve(2);
```



```
                     do {
                            press1=0.3636*(readport(0)-1);
                            press2=0.3955*(readport(2)-0.92);
```

```
                                        level=readport(1);
                                        time=gettime()-time_start;
                                        fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t%.2f\n",time,((level0-
level)/0.084),20*press1,20*press2,ampl);
                                        delay(0.05);
                                }while(level>low);

                                        closevalve(2);

                do {
                                        press1=0.3636*(readport(0)-1);
                                        press2=0.3955*(readport(2)-0.92);
                                        level=readport(1);
                                        time=gettime()-time_start;
                                        fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t0\n",time,((level0-
level)/0.084),20*press1,20*press2);
                                        delay(0.05);
                                }while(level<high);

                }}
    }

void openvalve(int valve_id)

    {
     if (valve_id ==1)
        {
         _outp(port+4,0xff);
         _outp(port+5,0xff);
         printf("VALVE 1 OPENED\n");
        }
```



```
     if (valve_id == 2)
        {
         _outp(port+6,0xff);
```

```
            _outp(port+7,0xff);
            printf("VALVE 2 OPENED\n");
           }
       }

  void closevalve(int valve_id)
      {
       if (valve_id == 1)
         {
          _outp(port+4,0x00);
          _outp(port+5,0x00);
          printf("VALVE 1 CLOSED\n");
         }
      if (valve_id == 2)
         {
         _outp(port+6,0x00);
         _outp(port+7,0x00);
         printf("VALVE 2 CLOSED\n");
         }
     }

float gettime()
     {
      clock_t clockNo;


      clockNo=clock();
      return clockNo/clk_per_sec;
     }

void delay(float tim)
   {
    clock_t clock0,clock1;
    clock0=clock();
    time0=clock0/clk_per_sec;
```

```
    do
    {
    clock1=clock();
    time1=clock1/clk_per_sec;
    }while((time1-time0)<=tim);
  }

void initialize()     //INITIALIZE THE CARD AND I/O PORTS
  {
  int c_reg,r_ch;
  int ch_val,val,st;
       int uni_pol,diff_inp;

  printf("Hardware verification ..............\n");



  val=0x70;
  _outp( port+9,val);
  c_reg=_inp(port+9);
         if (c_reg != val)
    {
    printf ("pcl-718 hardware verification failed!\n");
    exit(0);
    }
  _outp(port+8,1);     //CLEAR INTERRUPT REQUEST

  // READ A/D STATUS REGISTER
 uni_pol=0;
 diff_inp=0;
 st=_inp(port+8);
  if ((st & 0x40) == 0x40)
   uni_pol=1;
  if ((st & 0x20)!=0x20)
    diff_inp = 1;
```

```
  if (diff_inp==0)
     printf("Total 16 channels \n");
    else
      printf("Total 8 differential channels\n");

   if (uni_pol==0)
    printf("Bipolar Input \n");
   else
     printf("Unipolar Input\n");


start_ch=1;
      stop_ch=1;
 ch_val=stop_ch*16+start_ch;    /* SET SCAN CHANNEL VALUE */
_outp(port+2,ch_val);
r_ch=_inp(port+2);    /* READ BACK CHANNEL VALUE */
if (r_ch != ch_val)
{
   printf ("set scan channel failed!\n");
   exit(0);
}
              printf ("\nSTART SCAN CHANNEL= %d",start_ch);
   printf ("\nSTOP SCAN CHANNEL= %d\n",stop_ch);

              // INITIALIZE ANALOG OUTPUT PORTS
                _outp(port+4,0x00);
    _outp(port+5,0x00);
    _outp(port+6,0x00);
    _outp(port+7,0x00);
}
```

V

Timer controlled jigging operation for the new jig

```
/* '*********************************************************************
   '*  Program  : Jig3.c                        *
   '*  Version : 2.0                            *
   '*  Date     : 11/03/02                      *
   '*  Coded by : Vineet Kumar Dwivedi                     *
   '*  Under the Guidance of : Dr. B. K. Mishra              *
   '*********************************************************************/
//This program take the input of pt1,pt2, sensor only
//Uptime and Downtime can be defined which controls the motion

#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <share.h>
#include <conio.h>
#include <math.h>
#include <time.h>
#define clk_per_sec 1000.00F


void readdata(),output(),delay(float tim),initialize();
void openvalve(int valve_id),closevalve(int valve_id);
void checkpress();;
float gettime(),readport(int ch_id),convert(float pres);
void jig();
int start_ch, stop_ch, r_ch,ch_val;
// Global Variables
float uptime,downtime,pres,time0,time1,time_start,time_stop;
int n;
```

```
int port = 0x300;    //Initialize Base Address
FILE *fp,*ft;
float vol,vol_cri,HIGH,LOW;
char keyb;

void main()
{
  initialize();
  printf("Zig 1.1 Software by Vineet Kr. Dwivedi\n");
  readdata();
  fp=fopen("Data.xls","w");
        time0=gettime();
  do     //PERFORM THE EXPERIMENT
    {


      checkpress();     //CHECK THE COMPENSATOR PRESSURE
      time_start= gettime();

      jig();  //JIG THE BED 'N' TIMES

      time_stop= gettime();

      output();  //PRINT THE DETAILS  AFTER JIGGING

      printf ("ENTER [e]EXIT OR ANOTHER CONVERSION\n");
    }
  while((keyb=getche())!='e');
  fclose(fp);
}
```



```
void readdata()    // TAKE THE INPUT PARAMETERS
    {
     printf("\nInput the pressure in Kg/cm2   ");
```

```
    scanf("%f",&pres);
    vol_cri=convert(pres);
            printf("\nInput the UpTime in sec   ");
    scanf("%f",&uptime);
            printf("\nInput the DownTime in sec   ");
    scanf("%f",&downtime);
            printf("\nInput No. of times you want me to jig   ");
    scanf("%d",&n);
    printf("Pressure1=%f voltage = %f \n",pres,vol_cri);
    printf("No. of cycles = %d \n",n);
  }
 float convert(float pres)  //Give the voltage corresponding to Pr in Kg/cm2
 {
 return (pres*(2.5)+0.95);
 }


void output()
  {

    printf("Time taken for  %d  cycles =   %f   seconds\n",n,(time_stop-time_start));
    printf("Average  frequency  =  %f   cycles per min\n",60*n/(time_stop-time_start));

  }



void checkpress()
  {

    openvalve(1);
```



```
    do
      {
```

```
        delay(0.05F);
        vol = readport(0);
       }
     while(vol<=vol_cri);

            printf("vol_cri   = %f   vol  = %f\n",vol_cri,vol);
    closevalve(1);
    if(vol>=(1.1*vol_cri))
         {
      printf("WARNING: COMPENSATOR PRESSURE IS TOO HIGH\n");
      printf("Open the manually operated Valve for air exhaust ");
      exit(0);

    }
   }

float readport(int ch_id)
 {
  int st,dth,dtl,adl,adt;

     ch_val=ch_id*16+ch_id;    /* SET SCAN CHANNEL VALUE */
 _outp(port+2,ch_val);
 r_ch=_inp(port+2);    /* READ BACK CHANNEL VALUE */
 if (r_ch != ch_val)
 {
   printf ("set scan channel failed!\n");
   exit(0);
 }

     _outp(port,0);
     do
       st = _inp(port+8);
     while ((st & 0x80) == 0x80);
     dtl = _inp(port);
```

```
        dth = _inp(port+1);
        adl = dtl/16;
        adt = dth*16 + adl;
        ch_val =dtl-adl*16;
        if (ch_val == ch_id)
        return(adt*(5.0F/4096.0F));

  }



void jig()
   {
    int i;
    float gap,level,level0,height,high,low,time,press1,press2;
    level0=readport(1);
            level=0;

            for (i=1;i<=n;i++){
                openvalve(2);

                do {
                        press1=0.3636*(readport(0)-1);
                        press2=0.3955*(readport(2)-0.92);
                        level=readport(1);
                        time=gettime()-time_start;
                        fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t5\n",time,((level0-
level)/0.084),20*press1,20*press2);
                        delay(0.05);
                        gap=time-(i-1)*(uptime+downtime);
                }while(gap<uptime);
```



```
                        openvalve(3);
```

```
            do {
                        press1=0.3636*(readport(0)-1);
                        press2=0.3955*(readport(2)-0.92);
                        level=readport(1);
                        time=gettime()-time_start;
                        fprintf(fp,"%.2f\t%.2f\t%0.3f\t%0.3f\t0\n",time,((level0-
level)/0.084),20*press1,20*press2);
                        delay(0.05);
                        gap=time-(i-1)*(uptime+downtime)-uptime;
                  }while(gap<downtime);

            }
            closevalve(1);
    }

void openvalve(int valve_id)

   {
    if (valve_id ==1)
      {
       _outp(port+3,1);
       printf("VALVE 1 OPENED\n");
      }
    if (valve_id == 2)
      {
       _outp(port+3,2);

       printf("VALVE 2 OPENED\n");
      }
            if (valve_id == 3)
      {
       _outp(port+3,4);

       printf("VALVE 3 OPENED\n");
```

```
            }
        }

 void closevalve(int valve_id)
      {


          _outp(port+3,0x00);
           printf("VALVE  CLOSED\n");


      }

float gettime()
     {
      clock_t clockNo;


      clockNo=clock();
      return clockNo/clk_per_sec;
     }

void delay(float tim)
   {
     clock_t clock0,clock1;
     clock0=clock();
     time0=clock0/clk_per_sec;
     do
     {
     clock1=clock();
     time1=clock1/clk_per_sec;
     }while((time1-time0)<=tim);
   }
```



```
void initialize()     //INITIALIZE THE CARD AND I/O PORTS
   {
   int c_reg,r_ch;
```

```
int ch_val,val,st;
      int uni_pol,diff_inp;

printf("Hardware verification ..............\n");



val=0x70;
_outp( port+9,val);
c_reg=_inp(port+9);
        if (c_reg != val)
  {
  printf ("pcl-718 hardware verification failed!\n");
  exit(0);
  }
_outp(port+8,1);     //CLEAR INTERRUPT REQUEST

// READ A/D STATUS REGISTER
uni_pol=0;
diff_inp=0;
st=_inp(port+8);
if ((st & 0x40) == 0x40)
  uni_pol=1;
if ((st & 0x20)!=0x20)
  diff_inp = 1;



if (diff_inp==0)
   printf("Total 16 channels \n");
  else
   printf("Total 8 differential channels\n");
```



```
if (uni_pol==0)
  printf("Bipolar Input \n");
  else
```

```
      printf("Unipolar Input\n");


 start_ch=1;
       stop_ch=1;
  ch_val=stop_ch*16+start_ch;     /* SET SCAN CHANNEL VALUE */
 _outp(port+2,ch_val);
 r_ch=_inp(port+2);      /* READ BACK CHANNEL VALUE */
 if (r_ch != ch_val)
 {
    printf ("set scan channel failed!\n");
    exit(0);
 }
                printf ("\nSTART SCAN CHANNEL= %d",start_ch);
    printf ("\nSTOP SCAN CHANNEL= %d\n",stop_ch);

                // INITIALIZE DIGITAL OUTPUT PORTS
                 _outp(port+3,0x00);


 }
```

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